

MICROWAVE STERILIZATION OF BREAST MILK INFECTED WITH THE
AIDS VIRUS

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SYNOPSIS

The AIDS virus has been identified in breast milk (which is donated by expectant and recently delivered mothers in maternity hospitals). In maternity hospitals, where the facilities exist for the treatment of pre-term (premature) infants, breast milk is collected from mothers (even those who have not delivered premature babies) and it is used in its raw state to feed the children. The possibility of some of these mothers being infected with the AIDS virus is high in Third World countries. The premature infants have to be fed with breast milk as they are at risk of being infected if fed with commercial milk formulas. Commercially available milk sterilizers are available in Europe but they are very costly.

Research done in England has shown that the milk can be adequately sterilized (the HIV - (Human Immunodeficiency Virus) is completely deactivated) if the temperature of the milk is maintained uniformly in the temperature range of (56-57.5) °C for 33 min.

Dr C.W. Van Der Elst of the Department of Paediatrics and Child Health at Groote Schuur Hospital approached the Biomedical Engineering Department, who in turn, referred him Professor B.J. Downing of the Department of Electrical and Electronic Engineering. Following a meeting with Dr Van Der Elst at the Department of Electrical and Electronic Engineering, it was decided that a milk sterilizer should be made at a fraction of the price of commercially available ones.

Following a meeting with Professor Downing, the initial objectives of this were as follows:

1. To do research into the dangers of HIV infection through breast milk.
2. To understand and grasp the concepts of microwave heating by doing the necessary research into the topic.
3. To study and comply with the safety regulations (Electrical, Microwave and unit construction) which must be adhered to in the development of the equipment.
4. To design and build an item of hospital equipment which can deactivate the HIV in breast milk by providing a guaranteed control of milk temperature between (56-57.5) °C for 33 min.

Firstly, this dissertation comprises of a study of HIV infection of breast milk. It discusses and justifies why breast milk must be sterilized instead of simply feeding the preterm infants with the commercial milk formulas.

Then, a detailed set of project objectives is specified, followed by reasons for not using other heating methods such as a water-bath or heating element.

The sterilizer is to be used by hospital staff and as it poses hazards (Electrocution and Microwave irradiation), safety requirements for the unit must be adhered to. The safety requirements are laid down in the Government Gazette (Vol. 286 PRETORIA, 14 April 1989, No. 11823) under the HAZARDOUS SUBSTANCES ACT, 1973 (ACT No. 15 OF 1973).

A detailed investigation into the theory underlying microwave heating is then entered into. There is a discussion of four microwave heating models and an
 * elaboration on the most important mechanism responsible for energy conversion (dielectric resonance).

* Since the heat conversion process relies mainly on dielectric loss, the theory of dielectrics is enhanced upon. The permittivity of a dielectric is a complex constant. From this constant, information about the conversion of microwave energy into thermodynamic energy can be derived. The components which make up the permittivity however, are complex functions of a number of physical variables (liquid temperature, electric field strength and the frequency of the incident microwave field). The constant also contains information about the unwanted effect of reflected power (back towards the energy source (magnetron) , Thus, there is a discussion on the effects of these variables on the permittivity . The rate of heating of a microwave absorbing material is then discussed.

* To optimize heating of the milk (in terms of heating rate and uniformity) , the milk impedance must be matched to that of the source. Thus, the milks characteristic impedance is then calculated. As a result of tests performed, it is shown that the impedance of milk can be approximated to that of water. This fact is then used to design an applicator which can optimally and uniformly couple microwave energy into the milk/water.

*

The reasons for choosing a single-mode instead of a multi-mode microwave applicator are then discussed. The results indicate that uniform heating of a large load cannot be achieved in a multimode-cavity and that thermal run-away can occur. Temperature measurement in the multimode cavity is also difficult.

*

X

The single-mode applicator consists of a magnetron launching power into a launch waveguide. As a result of the possibility of some reactive mismatch, a length of tuningscrew waveguide is then added. By means of a Quarter-wave transformer, the load impedance is matched to the launch waveguide impedance. The Quarter-wave transformer matches out the resistive mismatch. The tuning screws cater for the reactive mismatch. After the microwaves are launched into the cylindrical waveguide, the fundamental TE mode in the cylindrical waveguide (TE_{11} mode) then propagates towards the load.

X

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Based on the temperature control needs of the unit, a suitable temperature measurement sensor is then chosen. A Platinum element (Pt100) RTD (Resistance Temperature Detector) is used due to it's superior accuracy, linearity and stability.

X

Following this, the electronic circuitry which is required to ensure that the milk or water is heated for the correct time is discussed, together with the interlock circuitry which affords the user safety from being radiated. The circuitry has been designed and tested.

Different power control techniques have been researched and tried. Continuous power control can be achieved if the supply voltage to the magnetron is altered. Optimal and Non-Optimal Integral-Cycle-Control techniques have been tried in order to alter input power to the magnetron-transformer. These have been discounted.

A saturable reactor can be used to continuously control the supply voltage to the magnetron-transformer. This means that accurate control of the magnetrons output power can be achieved. Excessive transformer heating does not arise as with the other methods.

The materials chosen for the construction of the unit are then discussed and diagrams showing the structural design are presented.

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LIST OF SYMBOLS

MMP	= Microwave Milk Pasteurizer
TE	= Transverse Electric Wave
D	= Dielectric Displacement
E	= Applied Electric field
$E_{x,y,z}$	= Electric field components in the x,y,z coordinates
$E_{r,\theta,\phi}$	= Electric field components in the x,y,z coordinates
P	= Polarization Vector
ϵ_0	= Permittivity of Free-Space
ϵ_r	= Complex relative dielectric constant
ϵ_r''	= Dielectric loss
ϵ_r'	= Dielectric constant
ϵ_s'	= Permittivity of dielectric at zero frequency
ϵ_∞'	= Permittivity of dielectric at infinite frequency
μ_0	= Permeability of Free-Space
μ_r	= Relative permeability
$\tan \delta$	= Tan Delta
Γ	= Complex propagation constant
α	= Attenuation constant
β	= Wave number
f_c	= Cutoff frequency for the TE_{mn} , TE_{np} modes
ω	= Angular excitation frequency of source
ω_m	= Angular excitation frequency of the dielectric
Z_0	= Impedance of Free Space
Z_0	= Transmission line characteristic impedance
Z_{water}	= Impedance of water
Z_{milk}	= Impedance of milk
Z_l	= Load impedance
Z_{launch}	= Characteristic impedance of launch guide
Z_{load}	= Load impedance
$Z_{\frac{1}{4}}$	= Impedance of quarter-wave transformer
Z_0	= Characteristic wave impedance
R	= Resistive component of Impedance
X	= Reactive component of Impedance
$X_{A,B,C}$	= Reactances
L_0	= Free-space wavelength
L_c	= Cut-off wavelength
L_{launch}	= Length of guide wavelength
L_{space}	= Length of the circular waveguide left open
$L_{transformer}$	= length of the transformer
L_g	= Guide wavelength
T_i	= Initial temperature of liquid
T_{final}	= Final Temperature of liquid
T_M	= Material temperature
dT	= Temperature rise

T_m	= Dielectric relaxation time
dt	= Time taken for heating
T_{osc111}	= The period of the internal oscillator of CD4541
T_{milk}	= Sterilizing period for the milk
T_{water}	= Sterilizing period for the milk using water
V_{+h}	= threshold at which the comparitor switches when comparitor output is high
V_{+l}	= Threshold at which the comparitor switches when comparitor output is low
V_{hyst}	= Hysteresis voltage
X'_{np}	= Bessel Constant
J_n	= n'th-order Bessel function of the First Kind
ν'	= Liquid viscosity
ρ	= Material density
k	= Boltzman's constant
$d\theta$	= Added heat
m	= Mass of sample being heated
C_p	= Heat capacity of the liquid being heated
P_{abs}	= Absorbed power
δ	= Penetration depths of microwave power
S_{11}	= Return Loss
ρ'	= Voltage reflection coefficient
$d\rho'$	= Difference in reflection coefficient

INTRODUCTION

AIDS is a life-threatening disease. As yet, no cure exists for a sufferer that has contracted the disease. At present, should a human contract the disease it is virtually certain that he/she will die.

At present, it is unknown whether the AIDS virus can be transmitted to an infant through mothers milk. Infants have acquired the virus (HIV - Human Immunodeficiency Virus), but the mode of transmission remains uncertain. The HIV may be transmitted transplacentally, by direct contact with the mother, or through breast milk.

Doctors would prefer to use pooled breast milk to feed premature babies (instead of commercial milk formulas). This is because an infant of less than 30 weeks gestation risks the chance of being infected with these milk formulas. At Groote Schuur Hospital, it was recommended that pooled breast milk should not be fed to pre-term infants as their chances of being infected by the AIDS virus is increased. However, not to feed infants breast milk may increase the risk of serious infection.

Pasteurization of the pooled breast milk will cut out the transmission of HIV through breast milk and eliminate the need for screening of potential milk donors.

The objectives of this dissertation are :

1. To do research into the dangers of HIV infection through breast milk.
2. To understand and grasp the concepts of microwave heating by doing the necessary research into the topic.
3. To study and comply with the safety regulations (Electrical, Microwave and unit construction) which must be adhered to.
4. To design and build an item of hospital equipment which can deactivate the HIV in breast milk by providing a guaranteed control of milk temperature between (56-57.5) °C for 33 min. This device will be referred to by the acronym MMP (Microwave Milk Pasteurizer).

The route followed in this thesis is as follows. A meeting with a Doctor from Groote Schuur Hospital was arranged. He discussed the requirements of the hospital and stressed their time and financial constraints. The problem of AIDS infection through breast milk was then examined. The theory of microwave heating was then researched followed by study of the safety requirements for hospital equipment. A microwave applicator and the electronic circuitry needed to run the MMP were then designed and tested. The MMP materials (plastics and metals) were chosen based on research done into their availability and suitability. The structural design of the MMP was then carried out. Research into the implementation of a cheap temperature control system was then completed.

Firstly, the dissertation discusses the problem of AIDS infection (of a premature infants) through breast milk. The reasons for **not** using breast milk alternatives are then discussed, followed by a presentation of presently available solutions for destroying the AIDS virus.

A comprehensive description of the thesis objectives and device requirements is then entered into, followed by a discussion of the reasons for using microwaves as opposed to other alternatives (such as a water-bath or a heating element).

As the sterilizer will be used in the hospital by hospital staff, safety of the equipment is a very important consideration. The unit uses both Electricity and Microwave energy, both of which, if not used carefully, can cause serious injury to the operator. It is for this reason that safety requirements, which must be adhered to (in terms of the law) , are then discussed.

* The means by which the microwave energy is converted into thermodynamic energy (in the form of heat) is then explained. Since the energy transfer process relies mainly on dielectric loss, the theory of dielectrics is then enhanced upon. An important constant which is a measure of the dielectrics properties (whether or not it will absorb microwave energy) is called its **permittivity**. This complex "constant" is in fact a function of a number of physical variables (temperature and electric field strength amongst others). Also, since its values (it is a complex value) determine the absorption (hence penetration depth) of microwave energy by the liquid, the dependence of the dielectrics on these physical variables is then evaluated. The rate of heating of a microwave absorbing material is then discussed.

*

* The rate and uniformity of microwave heating is dependent on applicator design (to ensure optimal coupling of power into the milk). Also, the applicator design relies on the impedance of the milk being known. The applicator design criteria are then discussed. This is followed by the theory which is used to characterize the impedance of the milk.

A load may have energy transferred into it using a multi-mode or single-mode cavity. These two methods are then evaluated and the results of tests performed are then covered.

The design of a single-mode applicator for irradiation of the milk load using microwaves at a frequency of 2.45 GHz is then described. This is followed by a discussion, comparison and finally a choice of a temperature measurement sensor for use in the MMP.

* The electronic (which incorporates timing and safety features) and electrical (magnetron power supply) circuitry which has been designed is then described. The techniques tested, which can be used to control the power (hence temperature) supplied to the breast milk are then reported on. This is followed by a description of the materials used in the design of the MMP and diagrams presenting its structural layout.

Finally, conclusions and recommendations are drawn based on the work done.

1. AIDS INFECTION THROUGH BREAST MILK

Human milk is used in maternity hospitals to feed preterm babies. Human milk differs considerably from cow's milk (in so far as proportions of main ingredients are concerned). It contains about the same amount of fat, about twice the amount of sugar (lactose) and about half the amount of protein. There is just enough calcium and iron for the baby's needs. Ordinary human milk contains about 2 percent protein, 4 percent fat and 8 percent sugar.

1.1 Risk of infection through breast milk

The HIV (Human Immunodeficiency Virus) antibodies have been identified in cell-free human milk [4]. The present system employed at Groote Schuur Hospital, is that recently delivered mothers are approached and asked to express as much milk as they can. The milk is then pooled and given to preterm babies (normally those weighing less than 1500g) in its raw state. The milk is neither frozen nor pasteurised.

There has been debate in medical circles whether or not to close milk banks on the basis that preterm babies might contract AIDS from infected donors. Some milk banks in England have already closed.[2]

Transmission of HIV from infected mothers to their infants may occur before, during or after birth. It has not been determined whether the virus can be effectively transmitted to the child through breast milk [5]. A large number of infants have been breast-fed (some for many months) without any evidence of acquiring HIV infection.

There is no conclusive evidence of breast milk transmission by seropositive (infected mothers) to their babies [5]. By 1987, it had been reported that five infants had been infected with the AIDS virus, where their mothers had only become infected after delivery [1]. This information was viewed with scepticism on the basis that it was not known how many similar situations there were, where the breast fed babies were not infected with HIV. Also, the existence of other risk factors such as the possible use of inadequately sterilised equipment was not known.[1]

The infectivity of the breast milk depends on a number of factors including the timing of the appearance of the virus in the milk, the strain of virus, maternal exposure to other viruses, the mechanism of transfer to the infant, the role of milk entering the nasopharynx, the integrity of mucosal barriers, the possible importance of maternal fluids other than milk, or the mothers nipple integrity and/or other maternal lesions [1].

Pooled breast milk for babies is donated by mothers that are not routinely screened for antibodies to the HIV. Also, the test for AIDS has limitations. The test detects the presence of certain antibodies (proteins in the blood) made by the body in response to the AIDS virus. The antibodies only appear in the blood two to twelve weeks after infection [6]. Thus, although the donating mother may have recently acquired the AIDS virus, the test may not pick up that she is infected. Compulsory screening of all potential donors might also reduce the number of donors, so pasteurisers have been developed to deactivate the virus in the milk [3].

1.2 The advantages of breast milk over its alternatives

The alternatives to using breast milk are using either a standard formula or a fortified preterm formula. There is evidence in the literature that the use of preterm formulas may have major clinical benefits. However, formula-fed infants have more vomiting and gastric stasis than those fed on human milk. Also, there is evidence that infants fed with milk formulas require more parenteral nutrition (where feeding is done using a CV (central venous) line) initially than those fed breast milk. The dangers of parenteral feeding include the possibilities of serious infection, the dangers of intravenous lines, embolism (blockage of arteries) and metabolic disturbance.

There are however, special cases when donor breast milk is of considerable value in neonatal intensive care [2].

Premature babies born after 28 weeks gestation can be fed by using a standard formula or a fortified preterm formula. It is difficult to establish enteral feeding (giving liquid by mouth or a nasogastric or nasoduodenal tube) for babies born at 24-28 weeks gestation [2]. In these cases, even when a special formula is used, some low-birth-weight infants have acquired concretions of the gut (severe constipation) which has necessitated the use of bowel surgery [2].

The advantages of using breast milk include the reduction of the incidence or severity of diarrhoea and gastrointestinal infection. There are also essential immunological and nutritional benefits [1]. There is also the possibility that the breast milk can provide protection against the progression of HIV-related diseases [1],[5]. Thus, the breast milk with its many anti-infective properties may actually protect against AIDS.

1.3 Available solutions to the problem

With the potential threat of infection in South Africa, precautions have to be taken in order to prevent the possible infection of the premature babies. It has been recommended that pooled breast milk should not be used to feed premature babies at Groote Schuur hospital.

The virus can be destroyed by pasteurising the milk. Two pasteurisers, designed in England exist which destroy the virus. These are the 'Oxford' pasteuriser by Vickers Medical (R45 000) and the 'Axicare' pasteuriser by Colgate Medical (R42 000) at 1988 prices. The Oxford pasteuriser maintains the temperature of milk between (54.5-55) °C for 30 min [3]. The Axicare pasteuriser maintains the temperature of the milk between (56-57.5) °C for 33 min [3]. As can be seen, there is leeway in the temperature control range which can be used to sterilize the milk. Since it is difficult to obtain references describing the reasons

required for the temperature ranges, it is assumed that above 57.5 °C, some damage will be done to milk constituents and possibly to the HIV antibodies. Further, it is assumed that below the lower limit of the temperature range, the virus will not be destroyed in the stipulated time.

Thus, pasteurisation of pooled breast milk eliminates the risk of transmission of HIV and screening for HIV antibodies becomes unnecessary [3]. The babies also have the previously discussed advantages of being fed with breast milk and don't have to be exposed to the possible dangers of being fed with preterm milk formulas.

2. PROJECT DESCRIPTION AND EQUIPMENT REQUIREMENTS

The objective of this thesis is :

1. To do research into the dangers of HIV infection through breast milk.
2. To understand and grasp the concepts of microwave heating by doing the necessary research.
3. To design and build an item of hospital equipment which can deactivate the HIV in breast milk.

A meeting with Dr C.W. Van Der Elst of the Department of Paediatrics and Child Health at Groote Schuur Hospital was arranged to discuss their requirements. Further, following a meeting with staff of the Division of (Non-Ionizing) Radiation Control of the Department of Health to discuss their safety requirements, the following guidelines for the MMP were laid out:

The device must :

- 1: Be designed to comply with the safety requirements (microwave and electrical) laid down by the necessary authorities (Hospital Technical Department, The Division of Radiation Control of the Department of National Health and Population Development and the SABS).
- 2: Have a capacity for approximately 2 litres of breast milk. This requirement fulfills Groote Schuur Hospital's needs. This is because typically 2 litres of breast milk will be used per day at Groote Schuur Hospital.
- 3: Provide a guaranteed control of milk temperature between (56-57.5) °C for 33 min. This temperature range and time limit has been used to sterilize breast milk successfully using the Axicare (COLGATE MEDICAL) pasteurizer [3].
- 4: Have the facility to allow the container housing the milk to be sterilised using boiling water. Preferably, the container used must be chosen so that components (e.g. fats) of the milk do not stick to the walls of the container.

- 5: Be designed taking careful note of economical constraints. The device will be designed for **volume production** assuming it may be used at all maternity hospitals which have the facilities to care for premature babies.
- 6: Facilitate the optimal transfer of microwave energy into the milk.
- 7: Allow the energy transfer process to result in uniform heating, thus ensuring the minimum (less than 1.5 °C) temperature variation within the milk volume.
- 8: Be easy to use (the device will be used by hospital nursing staff) and maintain.
- 9: Provide a sterilization procedure whereby the milk-housing can be sterilized with water at 100 °C.

3. JUSTIFICATION OF USING MICROWAVES ABOVE OTHER METHODS

A heating technique must be chosen that best fulfills the needs of the hospital. This section discusses heating techniques in terms of their advantages and disadvantages.

Three means of sterilisation have been considered. These include the use of a **waterbath**, a **hot element** and the use of **microwaves**.

Following discussion with hospital staff, the **waterbath** option has been discounted because:

- a: The temperature of water in a large waterbath is very difficult to maintain accurately.
- b: The time taken to sterilise the milk can be particularly long since the bath relies on heat conduction from the water-bath to the milk.
- c: Harmful bacteria in the water can easily be transferred to the milk.
- d: The waterbath is not considered a convenient device to use, as water is easily splashed around.
- e: A large quantity of water is required to be replaced periodically, so as to remove the bacteria which reside in the water. Boiling the water to remove bacteria does not work, as some of the bacteria can withstand temperatures in excess of 100 °C.

The hot element option has been discounted because:

- a: The temperature at the interface between the element and the milk is very difficult to control accurately.
- b: Conductive heating for quantities of milk greater than 2 litres is very slow.
- c: If the element is in direct contact with the milk, then the element is susceptible to corrosion.
- d: Heat transfer is slow because the heat transfer mechanism relies on conduction.
- e: Fats in the milk will stick to the heating element thereby necessitating frequent cleaning of the element. Superheating of the fats attached to the element also complicates temperature control.

* Whereas the above heating methods apply heat (a **disordered** form of energy) externally, **microwaves** make use of Electromagnetic energy, an highly **ordered** form of energy to facilitate the generation of heat internally.

The advantages of using microwaves are :

- a: Microwaves energy is an ordered form of energy that is controllable [7] i.e. one can have instant ON/OFF control.
- b: There is no thermal inertia from the energy source i.e. magnetron (if the cathode heating element is kept ON).

*

*

c: The energy transfer mechanism is the most efficient (see TABLES I & II below for a comparison of heating times for tests performed by the SHARP manufacturing company - heating tests were performed on 100ml and 1000ml distilled water loads). As illustrated, the heating time (to bring about boiling of the water) for microwaves is about 1/3 the time for a water bath (depending on the thermal properties of the container). The time required to convert electric wave energy into thermodynamic energy is **shorter** than the other heating methods. Another illustration of the efficiency of microwave heating is highlighted in the use of microwaves for material digestion. A typical wet digestion using a conductive heating method takes 1 to 2 hours, whereas microwave digestion can take 5-15 min [9].

*/

- d: The milk need not come into contact with any water (possibly containing bacteria harmful to a preterm baby), plastic (except the container in which it is housed) or metal element may be susceptible to corrosion.
- e: The microwaves penetrate into the milk and thus heat is also generated from **within** the milk.
- f: By proper selection and design of the microwave applicator, the energy can be focussed onto the milk.

g: The microwaves have a sterilisation effect (in so far as deactivating harmful bacteria) which is vastly better than the sterilisation ability of other heating techniques [8]. Whether or not the sterilisation effect arises from direct interaction of the microwaves with the bacteria, or as a result of the abrupt heating action is not known [8].

* h: Energy is not expended in heating the housing containing the breast milk.

*

HEATING METHOD	TIME TO BOIL
Microwave Oven	1 min. 40 sec.
Open Fire	4 min. 10 sec.
Water Bath	15 min.
Hot Air	20 min.

For 100 ml distilled water

TABLE I

HEATING METHOD	TIME TO BOIL
Microwave Oven	6 min. 25 sec.
Open Fire	22 min. 35 sec.
Water Bath	> 20 min.
Hot Air	57 min.

For 1000 ml distilled water

TABLE II

4. SAFETY OF MEDICAL ELECTRICAL EQUIPMENT

Shortly after the development of radiowave technology in the late nineteenth century, medical researchers discovered that radio-frequency (RF) electric current can affect living tissue.

Excessive RF electromagnetic radiation can produce a variety of adverse health effects. These include formation of cataracts of the eye, overloading of the thermoregulatory system (due to induced body heating), thermal injury, altered behavioral patterns, convulsions, nausea, decreased endurance, jaundice, internal bleeding and testicular damage (known to occur at or near the $10\text{mW}/\text{cm}^2$ level [10]).

The following sections highlight the requirements laid down in terms of South African Law (HAZARDOUS SUBSTANCES ACT, 1973 (ACT No. 15 OF 1973). It discusses the necessary safety requirements which have been designed for, in view of the possible harmful and fatal results.

4.1 General requirements in terms of the HAZARDOUS SUBSTANCES ACT, 1973 (ACT No. 15 OF 1973)

In terms of the HAZARDOUS SUBSTANCES ACT, 1973 (ACT No. 15 OF 1973) published in the Government Gazette (Vol. 286 PRETORIA, 14 April 1989, No. 11823.), any electronic product emitting microwaves e.g. (microwave ovens , door opening detectors), is termed a GROUP III HAZARDOUS SUBSTANCE.

4.1.1 Regulations relating to GROUP III Hazardous Substances

In order to make and sell an item of microwave equipment, certain conditions have to be fulfilled. Once the equipment is made and tested, an application for a licence must be made to the Director-General in writing. Together with the application, a report on the item of equipment must be submitted.

The report must include the date and place of manufacture, a model name and serial number. Included must be descriptions of :

- 1: The product radiation, the operating characteristics affecting the radiation and the intended use of the object.
- 2: The physical and electrical characteristics with special reference to shielding and electronic equipment.
- 3: The methods and procedures employed in testing and measuring of the equipment in regard to electronic product safety.
- 4: How the unit is tested for durability and stability.
If no testing or quality control procedure is applied, the basis on which these tests are deemed unnecessary must be described.

- 5: The standards and design specifications wrt electronic product safety.
- 6: The particulars of all warning signs, labels, instructions for installation, operation and use in respect of electronic product safety.

A further list of requirements and particulars required in terms of the ACT can be read in REF [11].

4.2 Equipment Safety Requirements

The Division of Radiation Control of the Department of Health have produced a document (a Draft Copy - Not yet Published) which gives guidelines for the production of microwave ovens. Also, the requirements laid out by the IEC (B.S. 5724 Part 1 1979) must be adhered to (this is a set of requirements for medical equipment laid down by the International Electro-Technical Commission (Switzerland), together with a description of how to test the equipment in terms of electrical safety). These two documents form the basis of safety principles adhered to, in the design of the Microwave Milk Pasteuriser (MMP).

The following sections summarize the importance of electrical and radiation safety as laid out by the guidelines.

4.2.1 Electrical

The MMP is classified as a CLASS I item of equipment in terms of the IEC (International Electro-Technical Commission) regulations, since it must provide protection against electrical shock and it cannot rely on BASIC INSULATION only. Means have to be provided so that the ACCESSIBLE CONDUCTIVE PARTS on the MMP are connected to the PROTECTIVE (EARTH) CONDUCTOR in the **fixed wiring** of the installation (This means that **no** ACCESSIBLE CONDUCTIVE PARTS of the MMP can become LIVE in the event of BASIC INSULATION failure).

The MMP is also classified as a TYPE B item of equipment as it has an INTERNAL ELECTRICAL POWER SOURCE.

As an additional safety feature, the equipment power supply cord/cable (whether detachable or not), must have a PROTECTIVE EARTH CONDUCTOR as part of the cord/cable and a MAINS PLUG **with** an earthing contact.

In terms of SUB-CLAUSE 14.4, at least the MAINS part of the equipment must be provided, in addition to the BASIC INSULATION, with ADDITIONAL protection.

PERIODIC CHECKING

The MMP will have to be checked periodically by hospital staff to see if any of the following SINGLE FAULT CONDITIONS have occurred.

These conditions include:

- 1: The interruption of one PROTECTIVE EARTH CONDUCTOR.
- 2: The interruption of one supply conductor of the equipment.
- 3: Short circuiting of the insulation in the case where the CREEPAGE DISTANCE and AIR CLEARANCE of such insulation is not in accordance with the values required in Sub-clause 57.10.
- 4: The failure of electrical/electronic components.
- 5: The failure of mechanical parts affecting the safety of the equipment.

TESTS PERFORMED BY THE HOSPITAL TECHNICAL DEPARTMENT

The continuous values of EARTH LEAKAGE CURRENT and ENCLOSURE LEAKAGE CURRENT are measured under the SINGLE FAULT condition when one supply conductor is interrupted at a time (Sub-clause 19.2 a).

The allowable EARTH LEAKAGE and ENCLOSURE LEAKAGE CURRENTS for TYPE B equipment are tabulated below (values are given in microamps).

CURRENT PATH	N.C.	S.F.C
EARTH LEAKAGE CURRENTS	0.5	1
ENCLOSURE LEAKAGE CURRENTS	0.1	0.5

N.C. - Normal Conditions

S.F.C.- Single Fault Conditions

TABLE III

In addition to fulfilling the above requirements, other electrical requirements must be complied with. These are listed below.

- 1: The power leads must conform with International colour code practice.
- 2: The unit should be fused after its mains ON/OFF switch.
- 3: The unit should also preferably be fused in the neutral conductor.
- 4: The fuse holders should comply with IEC standards.
- 5: There should be a high voltage warning label affixed internally to the EHT section.
- 6: The quality of the wiring, sensors, electrodes and components used must be of a high quality.
- 7: The instrument, being a source of electromagnetic interference, must not be able to cause the malfunction of other hospital equipment.
- 8: The instrument should preferably not be susceptible to fluctuations in the mains supply.
- 9: The colour of indicator lights used on the equipment must comply with IEC Standards.

- 10: A small light is required to indicate the status of operation of the unit.
- 11: The device must be equipped with at least two interlocks (mechanical or electrical) which ensure that :
 - a: The microwave power is interrupted **immediately** when any component (e.g. the door in the case of a microwave oven) of the unit is removed which could allow the escape of radiation.
 - b: There is no possibility that the device can radiate microwaves when that component is removed.
- 12: The interlocks used above must be **fail-safe** so that failure of **any** single component in the equipment will not cause the interlocks to become inoperative.

4.2.2 Microwave

The microwave unit shall, according to the conditions laid out in [12], pass the following tests.

When the device is operating in service with its output power adjusted to a maximum, the device should function in such a manner that :

- 1: The leakage radiation (measured with an instrument capable of measuring a power density of 1.0 mW/cm^2 to an accuracy of 2dB or better) at all accessible points 5 cm from the unit shall not exceed 1.0 mW/cm^2 (prior to continuous use at the hospital) and shall not exceed 5.0 mW/cm^2 when in continuous use. The measurements will be made with the device containing not less than 1 litre of milk/water.
- 2: The leakage X-ray radiation at all points 5 cm from the external surface must not exceed 0.25 mR.h^{-1} when averaged over 10 cm^2 .

The basic limits of exposure levels (power densities) are determined by the allowed SAR (Specific Absorption Rate $[\text{W.Kg}^{-1}]$) which are 0.4 W.Kg^{-1} for occupational exposure and 0.08 W.Kg^{-1} for the general public [13].

The reasons for choosing the above values have long been a series of debate and a the history surrounding the determination of the microwave power densities is given in REF [10].

The MMP must have a MICROWAVE RADIATION WARNING sign (bearing the words " Caution - Microwaves ") which is clearly visible and identifiable from 1 meter.

4.2.3 Unit construction

In terms of SECTION SEVEN - PROTECTION AGAINST EXCESSIVE TEMPERATURES, FIRE AND OTHER HAZARDS, SUCH AS HUMAN ERROR of the IEC standards (BS 5724 :PART 1 :1979), Clauses 42 (Excessive temperature), 43 (Fire prevention), 44 (Overflow, spillage, leakage, humidity, ingress of liquids, cleaning, sterilisation and disinfection), certain precautions have to be taken when constructing an item of hospital equipment.

Excessive temperatures have to be guarded against. Any metal handles, knobs, grips and the like which are held continuously by the user may not exceed 55 °C. Similarly, if those parts are held only for short periods of time, their temperatures may not exceed 60 °C. A list of allowable maximum temperatures of all possible materials used is given in the above reference.

A description of the tests performed is given in Sub-clause 42.4. It is important to note that since the MMP is a heating device, in terms of Sub-clause 42.4 Part 2, the test for excessive temperatures is done at 110 % of the rated voltage.

In terms of Clause 43, the item must have strength and rigidity so that in the event of mishandling, it does not present a fire hazard. Also, should an internal fire occur, no burning material should be able to escape the interior of the housing.

In terms of Clause 44, equipment which employs liquids, must have sufficient protection against hazards caused by overflow, spillage, leakage, humidity, ingress of liquids, cleaning, sterilisation and disinfection.

If liquid **overflows** the liquid storage chamber, the liquid overflowing from the liquid storage chamber shall not WET uninsulated LIVE PARTS or any electrical insulation which is likely to be adversely affected by the liquid. Equipment used where the likelihood of **spillage** arises, must be designed so that no LIVE PARTS or electrical insulation are wet in the event of spillage. Should **leakage** occur, no LIVE PARTS or electrical insulation should be wet. The tests prescribed to test for the above events are outlined in the sub-clauses of Clause 44.

Further, to make the unit safe, the unit should be well finished, robust and there should be no sharp protuberances.

The panel markings should stand up to a petroleum spirit test (TEST done at the hospital). The unit should be designed so that it is easy to repair and spare parts should be readily available.

5. MICROWAVE HEATING THEORIES

* The rapid heating of the milk is made possible because of the ability of the water in the milk to efficiently absorb energy (due to the fact that it is polarizable). There are a number of explanations as to how the microwave energy is transferred from the Electromagnetic wave to Thermodynamic energy.

The following sections discuss **how** heat is generated in microwave absorbing materials containing ions and dipoles. Section 5.3 discusses dipoles, the components which are most affected by microwaves at **low temperatures** [7]. Section 5.4 discusses complex permittivity, the two components of which affect the transmission of microwaves through the dielectric. Permittivity also has an effect on the load impedance (breast milk), since the load impedance is a function of the two constants. Load impedance is discussed in Section 6.2 .

5.1 Water polarization

When the water is placed in an electric field, its polarizability is affected. There are four mechanisms [22] of polarization and the total polarization can be expressed as :

$$\alpha_{tot} = \alpha_{el} + \alpha_{ion} + \alpha_{dip} + \alpha_{int} \quad (1)$$

Where :

α_{el} = electronic contribution due to displacement of electronic cloud from nucleus.

α_{ion} = due to movements of ions wrt other ions

α_{dip} = due to presence of permanent dipoles in liquid

α_{int} = due to random layered inhomogeneities in the liquid.

The microwaves mainly disturb the dipole polarization [22].

The water molecule H_2O , having a strongly electro-positive oxygen atom, attracts the free negatively charged electrons towards itself. As a result, the oxygen end of the molecule becomes negative and the hydrogen ends become positive. The resultant charge distribution is called an electric dipole.

5.2 Heating models

5.2.1 Dipole model

The electric field created by the microwave source is able to apply a torque to the water molecules which forces the dipole moments of the molecules to align themselves with the applied electric field. When the applied electric field is removed, the molecules return to random (Brownian) motion.

The first attempt at describing the energy transfer mechanism was by P.J.W. Debye (a Dutch physicist). He made known the important fact that water molecules cannot rotate instantaneously in order to align with the electric field since they have mass. Retarding forces due to other molecules around them also affect the rotation.

Whether or not the molecules can follow the changing electric field is determined by the response time of the water molecule. At low frequencies, the time taken for the external field to change is longer than the response time of the water molecules so the dipole moments keep in phase with the electric field. At too high frequencies, the response time of the water molecules is too slow and the dipoles cannot follow the rapidly changing field.

At microwave frequencies, the time in which the field changes is about the same as the response time of the water molecules. The resulting polarization lags behind the electric field. The lag indicates that the water absorbs energy from the microwave field [14].

5.2.2 Spherical model

An explanation for the energy transfer is achieved if the water molecule is modelled as a sphere. The sphere is rotated due to the action of the applied electric field. At low frequencies, the drag due to surrounding molecules is too small. At high frequencies, the drag due to surrounding molecules is so high that the molecules do not rotate.

At microwave frequencies, the sphere rotates fast enough to encounter drag. An explanation for the energy transfer is as follows. Suppose that there is electrical force equilibrium (this creates the viscous drag) between a water molecule and its surrounding water molecules. The application of the electric field will disturb the electrical equilibrium and thus increase the random motion (thereby increasing thermodynamic energy).

5.2.3 Bond Reformation Model

Another theory of energy transfer is that ordinarily water molecules form groups (of 2,3,4,5). The combinations of one of these groups (in particular a combination of 3 H₂O molecules) makes them susceptible to be affected by an applied electric field.

Oxygen has two low-potential energy sites where attachments by the hydrogen atoms of surrounding H₂O molecules are most likely to occur [14]. The torque arising due to the applied field may be sufficient to break the bond at the **higher potential-energy site** on the oxygen atom. The hydrogen atom may then form another bond at the **lower potential-energy site** of the two. Obeying the principles of energy equilibrium, the lowered potential energy must mean that the kinetic energy of the system increases. This increase in kinetic energy manifests itself as an increase in the random motion of the molecules (i.e. as an increase in temperature).

5.2.4 Ionic Model

The presence of ions in a liquid also facilitates the production of heat. In the case of salt for example, the positive Sodium ions Na^+ , are surrounded by up to four water molecules. The negative Chlorine ions Cl^- , are surrounded by up to seven water molecules [14].

The microwave electric field forces the hydrated positive sodium ions in the direction of the field and the hydrated negatively charged chlorine ions in a direction opposite to the electric field. There is thus a flow of current. The collision of the hydrated ions with other water molecules increases their random motion, and thus the water heats up [14]. The heat production is thus I^2R [15] loss due to current flow against the resistance (presented by the other water molecules) to the ion flow.

The ionic losses depend on size, charge and conductivity of the dissolved ions and are dependent on the solvent (i.e. the molecules surrounding the ions) molecules. The dissipation factor changes with temperature as a result of the temperature dependence of ion mobility and concentration [15].

5.3 Dielectric properties of Dipoles

Dielectrics are solid and liquid non-conducting materials. They have atomic charge carriers, but they are not freely mobile. They are however, free to be displaced due to the influence of an applied electric field.

- * The relative dielectric constant of a material ϵ_r' is used to give an indication of the amount of free charge which accumulates at the surface of the dielectric when an electric field is applied.

The relationship between the resulting orientation of the dipole moments and the electric field E is denoted by the field parameter D (the dielectric displacement) through :

$$D = \epsilon' \cdot E = \epsilon_0 \cdot \epsilon_r' \cdot E \quad (2)$$

The resulting polarization P of the dielectric is determined by D and E through :

$$P = D - \epsilon_0 \cdot E \quad (3)$$

X

However, when a time dependent electric field is incident on the dielectric, say :

$$E = E_0 \cos \omega t \quad (4)$$

then D will generally not be in phase with E (as a result of the viscous drag discussed above).

The result is a dielectric displacement:

$$\begin{aligned} D &= D_0 \cdot \cos (\omega t - \phi) \\ &= D_0 \cdot \cos \phi \cdot \cos \omega t + D_0 \cdot \sin \phi \cdot \sin \omega t \\ &= D_1 \cdot \cos \omega t + D_2 \cdot \sin \omega t \end{aligned} \quad (5)$$

$$D_1 = \epsilon' \cdot E_0 \quad (6)$$

$$D_2 = \epsilon'' \cdot E_0 \quad (7)$$

X

From the above equations we obtain the very important equations:

$$\tan \delta = \frac{\epsilon''}{\epsilon'} \quad \text{Tan Delta} \quad (8)$$

$$\text{and } \epsilon_r = \frac{\epsilon^*}{\epsilon_0} = \epsilon_r' - j \cdot \epsilon_r'' \quad \text{Complex dielectric constant} \quad (9)$$

$$\text{Thus } D = \epsilon^* \cdot E = \epsilon_0 \cdot (\epsilon_r' - j \cdot \epsilon_r'') \cdot E \quad (10)$$

The factor ϵ'' is termed the "dielectric loss".

The dielectric constant ϵ' is a measure of the dielectric's ability to obstruct the travelling microwave energy (in terms of speed). The loss factor is a measure of the dielectric's ability to dissipate that energy [15].

The greater the dissipation, the less is the penetration (at a given frequency).

*

5.4 Permittivity and factors which affect it

5.4.1 Simple dipole liquids

Section 5.3 shows the theory relating to the manner with which the dielectric affects the transmission of EM microwave energy. As can be seen, the amount of loss incurred by the microwaves which are incident on the dielectric, is dependent on both ϵ_r' and ϵ_r'' . In fact, both of these constants are dependent on a number of factors.

These factors include the material type, density and the excitation frequency. Also, the complex dielectric constant is a non-linear function of electric field strength $E(r)$ (where r is position), the material temperature T_M . Further, it is dependent on the time history of material temperature and applied electric field [16].

thus $\epsilon^* = f(w, E, T_M, r)$

As the material is heated, the dielectric constant may exhibit hysteresis in both temperature and electric field strength. It can also change as a result of chemical changes [16].

When a dipole reverts back to unregulated thermal equilibrium, after it has been acted upon by an external electric field, the time it takes to revert back to 63% of total disorder is termed the dielectric relaxation time (τ_m) of the molecule. This is denoted as :

$$\tau_m = \frac{1}{\omega_m} \quad (11)$$

where ω_m is the angular excitation frequency of the dielectric.

* When the excitation frequency of the microwave source approaches that of the dielectric, a peak in dielectric loss occurs i.e. there is maximum absorption of the microwave energy by the dielectric.

*

The manner in which the two dielectric constants change with frequency was described by Debye [17] and they are :

$$\epsilon'(\omega) = \epsilon_{\infty}' + \frac{\epsilon_s' - \epsilon_{\infty}'}{1 + \omega^2 \cdot \tau_m^2} \quad (12)$$

$$\epsilon''(\omega) = \frac{(\epsilon_s' - \epsilon_{\infty}') \cdot \omega \cdot \tau_m}{1 + \omega^2 \cdot \tau_m^2} \quad (13)$$

$$\tan \delta = \frac{\epsilon''(\omega)}{\epsilon'(\omega)} = \frac{(\epsilon_s' - \epsilon_{\infty}') \cdot \omega \cdot \tau_m}{\epsilon_s' - \epsilon_{\infty}' + \omega^2 \cdot \tau_m^2} \quad (14)$$

The bell-shaped curve of ϵ'' (as shown below) is achieved when $\omega \cdot \tau_m = 1$.

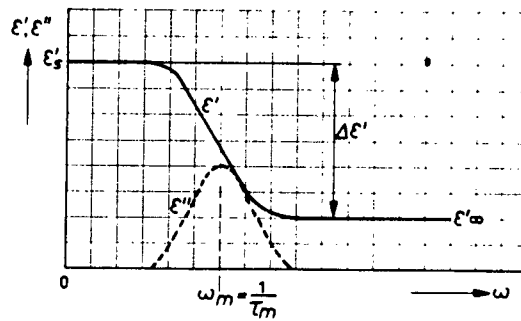


FIGURE (1)

Further, an illustration of the dependence of the two constants on frequency was shown in the plane by Cole-Cole [18] to be as illustrated below (right). As is illustrated by the diagram on the left, the dipole molecule can be modelled by an electrical circuit.

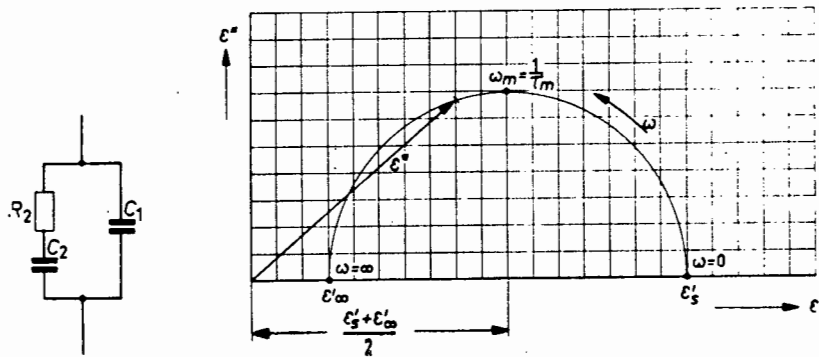


FIGURE (II)

If one considers the sphere modelling, where the sphere has a radius r , and the medium has a viscosity ν' , then Debye showed that the absorption time is:

$$\tau_m = \frac{4 \cdot \pi \cdot \nu' \cdot r^3}{k \cdot T} \quad (15)$$

where: k is Boltzman's constant

T is the temperature of the medium

The above equation shows how to determine the variation of the natural frequency of the medium with temperature.

A

The graph below shows how $\epsilon'(f)$ and $\epsilon''(f)$ vary with temperature for a typical dipolar substance. As expected, the excitation frequency of the medium increases with temperature.

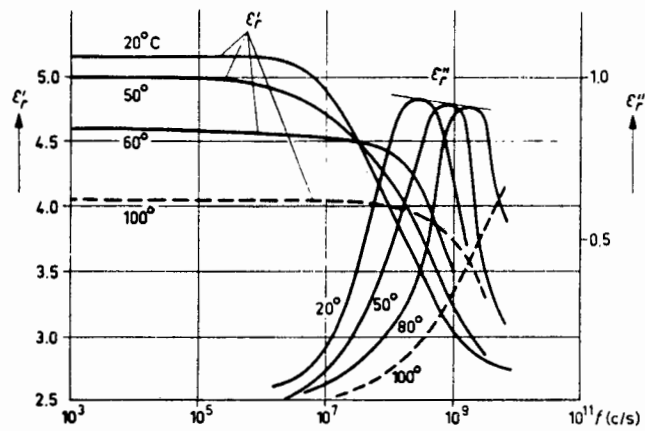


FIGURE (III)

5.4.2 Hydrated macromolecules and Complex dipole mixtures

There are harmful effects when microwaves radiation interacts with biological material [19] such as denaturing of proteins and a reduction in vitamin content (this is due to heating effects).

Real liquids are not comprised purely of a single liquid. The deposition of microwave energy is largely determined by the water content. Biological materials (such as human milk) also comprise of macromolecules which get hydrated and thus give rise to **bound water**.

Models have been created for these hydrated molecules. The models consist of a spherical shell of **bound water** surrounding a spherical core.

When the power deposition per unit volume for **bound water** is compared with that for **free water**, it is found to be significantly higher than that for free water for frequencies up to 1 GHz [19].

It was found that the static permittivity of the shell of bound water gives rise to a dispersion in the relaxation frequency in the range 100-1000 MHz in contrast to the relaxation frequency of about 26 GHz for free water [19].

Grant, Sheppard and South 1975, 1978 and Schwan 1977 [19] showed that biological samples having a large amount of bound water are expected to absorb relatively more microwave energy below 5 GHz than if all of the aqueous components were in a free state.

If there is a mixture of two dipoles in the liquid, the result is that the loss factor of the liquid is determined by the sum of the two loss factors [17]. This is illustrated in the graph below for two different dipoles 1 & 2.

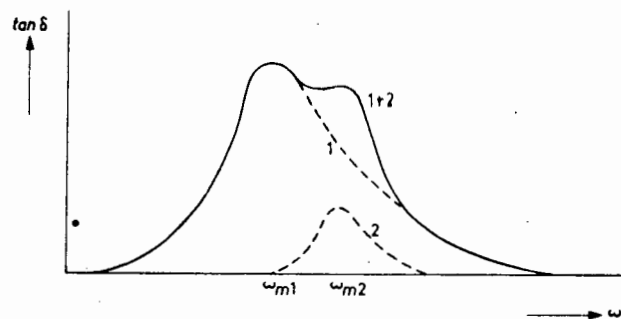


FIGURE (IV)

5.5 Heating Rate Formulas

It is possible to derive approximate formulae which give insight into the rate of heating of a liquid. If it assumed that microwave energy from a uniformly incident wave front is converted into thermodynamic energy in the liquid, then the added heat $d\theta$ to cause a temperature rise dT is:

$$d\theta = m \cdot C_p \cdot dT \quad (16)$$

where m = the mass of sample being heated

C_p = the heat capacity of the liquid being heated

Thus the power needed for such a heating rate is :

$$P = \frac{d\theta}{dt} = m \cdot C_p \cdot \frac{dT}{dt} \quad (17)$$

Further, the above equation can be written as a power density formula :

$$\frac{P}{V} = \rho \cdot C_p \cdot \frac{dT}{dt} \quad (18)$$

where : ρ = material density

But, it can be shown from Maxwell's equations that the instantaneous power dissipated in a liquid (or any material) is :

$$P_{abs} = \int_V \sigma |E|^2 dv \quad (19)$$

E = RMS value of electric field
inside the material

$$\sigma = \sigma (\text{ionic}) + \sigma (\text{dipole}) \quad (20)$$

$$\text{where : } \sigma (\text{dipole}) = w \cdot \epsilon'' (\text{dipole}) \quad (21)$$

The main contributing conductivity is the dipole conductivity [7] thus, the absorbed power in a volume V can be given as :

$$P_{abs} = \int_V w \cdot \epsilon'' \cdot |E|^2 dv \quad (22)$$

If the EM wave is relatively uniform through the interaction region, then the following approximation can be made :

$$\frac{dP}{dV} \approx 2 \cdot \pi \cdot f \cdot \epsilon'' \cdot |E|^2 \quad (23)$$

If equations (18) and (23) are compared, it follows that :

$$\frac{dT}{dt} \approx \frac{2 \cdot \pi \cdot f \cdot \epsilon'' \cdot |E|^2}{\rho \cdot C_p} \quad (24)$$

note that: $\epsilon'' = \epsilon_0 \cdot \epsilon_r''$

It must be considered that a number of simplifications have been made in order to derive equation (24). Variations in permittivity with temperature and electric field strength have been ignored. The variation of Electric field strength in the x, y and z directions have been ignored. C_p is also a function of temperature. Other effects such as convection and conduction have been ignored. However, the equation gives us a fundamental insight into the rate of heating achievable.

The equation tells us that in order to increase the heating rate, a higher frequency oscillator must be used.

However, we cannot be too hasty to increase frequency as the penetration depth δ (where the incident power is reduced to $\frac{1}{2}$ of initial value {see (25)}) decreases as frequency increases (thus there is the risk of thermal run-away due to an uncontrolled rate of surface heating).

$$\delta = \frac{3.L_0}{8.686 \cdot \pi \cdot (\epsilon''/\epsilon') \cdot (\epsilon_r'/\epsilon_0)^{1/2}} \quad (25)$$

[23]

Equation (24) shows that the rate of heating increases with the square of the electric field (present inside the liquid).

6. THEORY OF IMPEDANCE MATCHING FOR THE OPTIMAL TRANSFER OF ENERGY TO THE LOAD

6.1 Applicator design criteria

It is important to consider applicator design, for unless the liquid being radiated with microwaves is uniformly heated, it is possible to get local heating rates which could exceed the bulk heating rate of the liquid [7,17]. This would lead to changes in impedance and hence further the non-uniformity of heating. This is known as thermal run-away.

By correct design of the applicator, efficient coupling of the microwave energy into the milk can be achieved.

*

The microwave system can be modelled by an equivalent circuit (Figure (V) on the following page). It consists of a constant frequency oscillator (the magnetron), the transmission line (coaxial line coupling power from the magnetron), the applicator (waveguide) and the load (breast-milk).

For the efficient transfer of energy from the microwave power source to the load, the output admittance of the magnetron Y_0 and the input admittance of the material loaded applicator admittance Y_{in} must be equal to the transmission line characteristic admittance Y_0 .

*

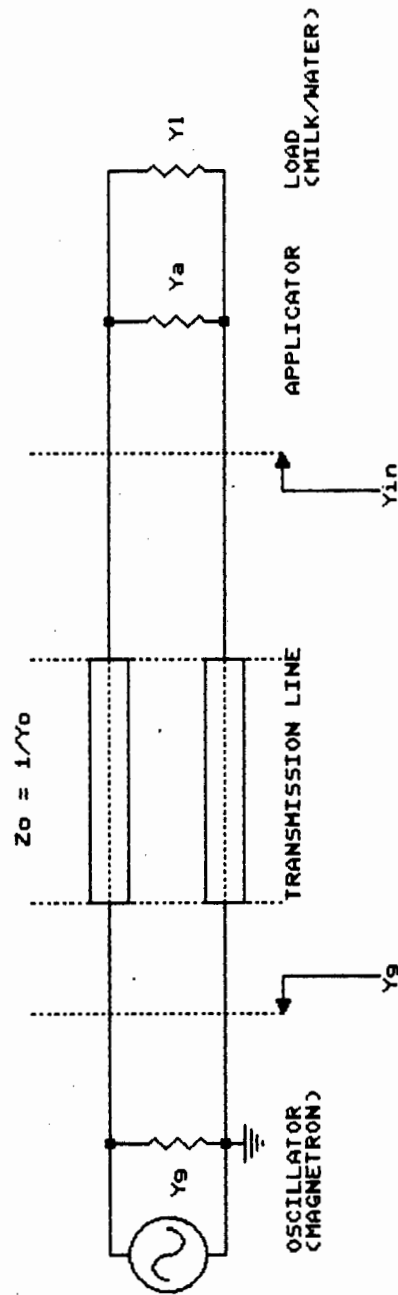


FIGURE (V)

6.2 Impedance of lossy dielectrics

In order to design the microwave applicator system, as seen above, it is desirable to have the material loaded applicator admittance Y_{in} be equal to the transmission line characteristic admittance Y_0 .

This demands a understanding of what the impedance / admittance of the milk (lossy dielectric) is .

The impedance Z of the milk has two components, a real part R (the resistive component) and an imaginary part X (the reactive component).

thus $Z = R + j X$

This section shows that the reactive component of the impedance is negligible compared to the resistive component. Knowing this, the design of the applicator is considerably eased i.e. matching to remove the reactive component of the milk is simplified.

*

The presence of dissipation in the dielectric medium (milk) results in an imaginary propagation constant which will for the purposes of this thesis be denoted by Γ . As a result of this imaginary propagation constant, the transmission-line equations may be written as :

$$\begin{aligned} \frac{dV}{dz} &= -\Gamma \cdot Z \cdot I \\ \frac{dI}{dz} &= -\Gamma \cdot Y \cdot V \end{aligned} \quad (26)$$

Z and Y are the impedance and admittance respectively. V and I are the microwave induced voltage and current and z is the direction of microwave propagation.

The propagation constant may be written as :

$$\Gamma = \alpha + j \cdot \beta \quad (27)$$

where α = the attenuation constant

$$\beta = \frac{2 \cdot \pi}{L_g} = \text{the wave number} \quad (28)$$

, L_g = the guide wavelength λ_g

The characteristic impedance is thus :

$$Z = \frac{1}{Y} = \begin{cases} \frac{j.w.\mu}{\Gamma} & \text{for H-modes} \\ \frac{\Gamma}{j.w.\epsilon} & \text{for E-modes} \end{cases} \quad (29)$$

In a wave guide where the cutoff wavelength $L_c > L_o$ the free space wavelength, the attenuation constant is :

$$\alpha = \frac{\pi \cdot L_o \cdot \epsilon''}{L_o^2} = \frac{2 \cdot \pi}{L_o} \cdot \sinh \left[\frac{\sinh^{-1} x}{2} \right] \quad (30)$$

and the wave number is :

$$\beta = \frac{2 \cdot \pi}{L_o} \cdot \cosh \left[\frac{\sinh^{-1} x}{2} \right] \quad (31)$$

$$\text{where : } L_o = \frac{L_o}{\sqrt{\epsilon' - \left[\frac{L_o}{L_c} \right]^2}} \quad \text{and} \quad x = \epsilon'' \cdot \frac{L_o^2}{L_o^2}$$

L_o = the free space wavelength

L_c = the cut-off wavelength

The impedance of interest in the case of the milk-loaded waveguide is that of the H - modes (i.e. TE modes).

In this case :

$$Z = Z_0 \frac{L_0}{L_c} \left[\cosh \left[\frac{\sinh^{-1} x}{2} \right] + j \cdot \sinh \left[\frac{\sinh^{-1} x}{2} \right] \right] \quad (32)$$

where :

$$Z_0 = \sqrt{\frac{\mu_0}{\epsilon_0}} = \text{Impedance of Free Space} = [120.\pi] \Omega$$

$$\text{but } \left[\frac{L_0}{L_c} \right]^2 = \frac{1}{\epsilon' - \left[\frac{L_0}{L_c} \right]^2} \approx \frac{1}{\epsilon'} \quad (33)$$

if $L_c \gg L_0$ for $\epsilon' \gg 1$

then :

$$Z = \frac{Z_0}{\sqrt{\epsilon'}} \left[\cosh \left[\frac{\sinh^{-1} x}{2} \right] + j \cdot \sinh \left[\frac{\sinh^{-1} x}{2} \right] \right] \quad (34)$$

also, when : $L_c \gg L_o$

$$\text{then } x \approx \tan \delta = \frac{\epsilon''}{\epsilon'} \quad (35)$$

For the purposes of this section, calculations will be performed using the **dielectric constant** and **loss factors** for water (as a function of temperature). The reasons are explained in Chapter 7.

The following is a table (Table IV) of dielectric constants, $\tan \delta$ and real and imaginary impedances for water as a function temperature at 3 GHz. The dielectric constants and $\tan \delta$ are from [17].

Temperature	ϵ'	* $\tan \delta$	Re[Z]	Im[Z]
°C	p.u.	p.u.	Ω	Ω
15	78.8	2050	42.47	4.33
25	76.7	1570	43.1	3.37
35	74.0	1270	43.8	2.78
45	70.7	1060	44.8	2.37
55	67.5	890	45.9	2.04
65	64.0	765	47.1	1.8
75	60.5	660	48.5	1.6
85	56.5	547	50.2	1.37
95	52.0	470	52.3	1.23

TABLE IV

* $\tan \delta \times 10^{-4}$

As illustrated above, the imaginary impedance (reactive component) is a small fraction of the real impedance (resistive component) over 15 °C to 95 °C. Thus, for the purposes of matching, the load will be considered resistive.

As a matter of interest, there are empirical formulae available which model ϵ' and ϵ'' as a function of temperature (for 2.45 GHz). These formulae are given in [21]. ϵ' can be modelled as a permittivity which is a linear decreasing function of temperature and ϵ'' can be modelled as a loss term which is an exponentially decreasing function of temperature.

7. MICROWAVE APPLICATORS

Most heating of materials takes place in either nonresonant applicators such as single or multipass slotted waveguides or in multimode resonant cavities [16]. The most popular applicator is the overmoded/multimode cavity (" the microwave oven ") . Some applicators have employed resonant cavities using TM modes [16].

The purpose of this chapter is to highlight the differences between the different applicators and discuss reasons for the preferred choice of one over of the other.

7.1 Multimode

Microwave ovens or continuous microwave processing tunnels behave as multiresonant systems. A plane wave emanating from the microwave source (typically a magnetron) will reflect off the walls of the cavity until it interacts with the object being heated. Thus energy utilization efficiency in the cavity is good because the waves travel inside the cavity until they are finally absorbed. The feed structure is designed so that minimum reflected power (from the load) will return to the source. ✱

As a result of the resonant behavior of the oven, a **varying power density** is set up in the x, y, z coordinates of the oven. These minima and maxima can lead to the formation of temperature extremes in the load [7]. Heat conversion efficiencies in these systems can vary typically between 50-95%. Multimode systems are used in preference to single mode systems if the load is irregular in shape. This is because multimode excitation reduces coupling sensitivities to the variety of geometric shapes placed in the cavities [16].

Associated with each mode is an impedance. A number of ~~*~~ ~~X~~ modes resonant in the cavity will have a variety of impedances. Thus, as the load parameters change (temperature hence permittivity hence impedance), different modes will couple power more efficiently into the load. The modes which have impedances closest to the impedance of the load will couple their power most efficiently into the load. New modes will take over as the load temperature changes.

The multimode cavities are used frequently as a result of their low cost, ease of construction, and their adaptability to heating many different loads [7].

Multimode applicators are in general open loop processing systems, owing to the difficulties encountered when attempts are made to measure temperature [7].

7.2 Single mode

Waveguide applicators cause a unidirectional flow of microwave energy in the waveguide. There are minor multiple reflections which occur due to material boundaries [7].

Also, the electromagnetic fields in a waveguide are not very dependent of the material in the waveguide [7].

To achieve temperature control, it is important that good heating uniformity, good coupling efficiency and a means of electrical feedback. These can be achieved using single mode systems.

7.3 Evaluation and tests on:

7.3.1 Multimode cavities

Although minima and maxima can occur in a standard microwave oven, as discussed in Section 7.1 , it is possible to even out the field heating effects within the cavity by using a rotisary (turntable) or a mode stirrer (rotating reflectors) [7].

To test the effectiveness of the heating, tests were performed using a National Microwave oven (with turntable) on different sized containers and different (in terms of viscosity) liquids. The two containers had different aspect ratios (see the figure (VI) below):

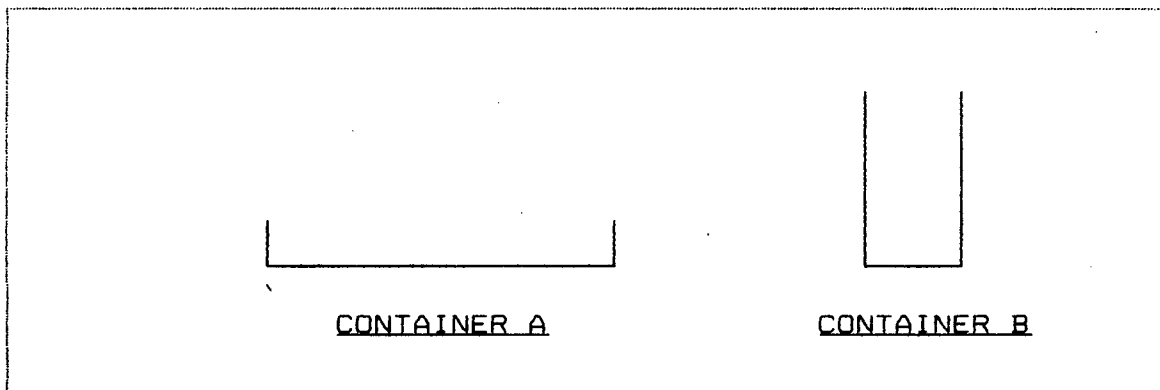


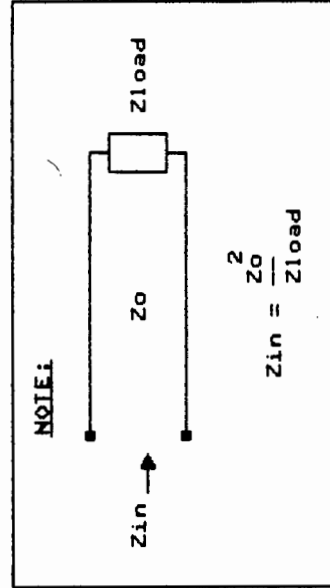
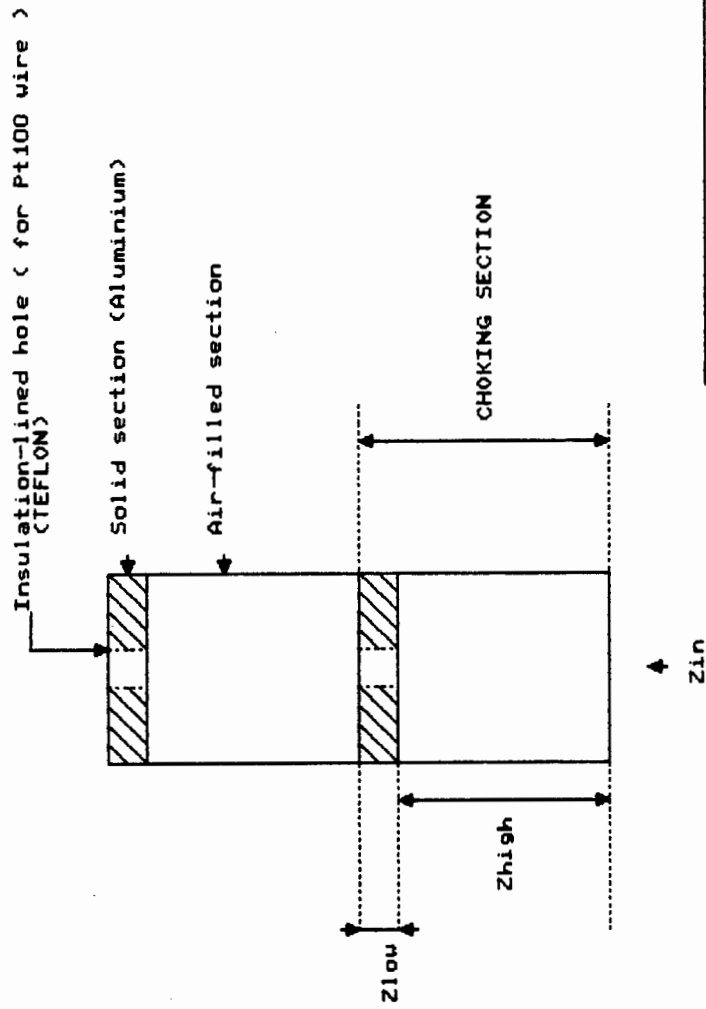
FIGURE (VI)

Container A had dimensions (length x height) (20 cm x 2 cm). Container B had dimensions (8 cm x 15 cm). The two liquids used were milk (low viscosity) and condensed soup (high viscosity).

It was found that for both containers and for both liquids, the temperature (measured when the microwave oven was OFF) at the centre was always markedly cooler than that at the edges. In fact it was possible to get the soup at the edge of Container A to boil while the centre remained cool.

Thus, it appears that the "uniform" field which can be set up theoretically (under no-load conditions) tends not to be sustained when the cavity is loaded. The electric field at the edge of the container is larger than that at the centre. So, in order to achieve uniform heating, a small load would be required.

Further, an attempt was made to measure the temperature within the multimode cavity (microwave oven). A hole was drilled in the top of a standard microwave oven. A multistage choke system (made of Aluminium) was used to choke the microwaves which couple onto the thermocouple lead (see Figure (VII)).



SKETCH OF CHOKING SYSTEM USED TO PREVENT
MICROWAVE LEAKAGE ALONG THERMOCOUPLE WIRE

FIGURE (VII)

The impractical results were that a choking system with a length in excess of 20cm was required to choke the signal. Further, since it is possible that the electric field lines can align themselves with the stainless steel thermocouple probe, self heating (due to microwave induced currents) of the thermocouple probe could not be avoided. This was evident when the probe alone was placed in the cavity.

Also, it would be impractical to have a thermocouple probe immersed in a liquid which is being rotated by a rotisary.

7.3.2 Single mode cavities

Tests have been performed in a single mode cavity to ascertain the difference in impedance between milk and water, as no information is available on the permittivity of breast milk.

The diagram on the following page illustrates the experimental setup.

The aluminium container housing (a cylindrical waveguide of diameter 98 mm) the milk/water rests on a length of polyethylene. With the system connected to the network analyser and the unit filled with water, a match was effected using the matching screws. The container was filled with enough water, so that if more water was added, the parameter S_{11} (a measure of the reflected power) was not affected. The frequency sweep was set from 2.4 GHz to 2.5 GHz and the frequency examined was 2.45 GHz.

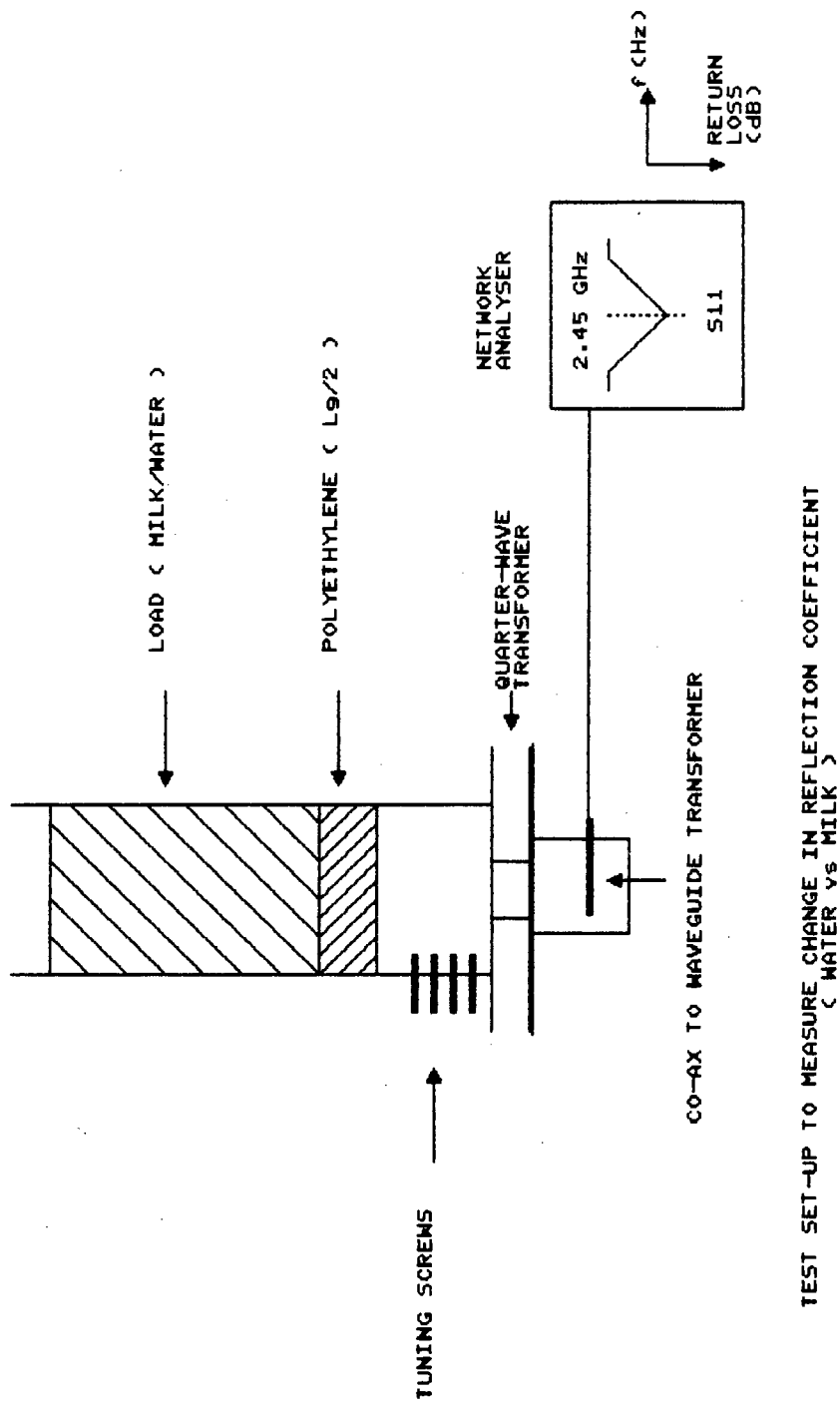


FIGURE (VIII)

A measurement of $S_{11} = -2.6$ dB was first made with the waveguide filled with water. When the water was replaced with milk, a measurement of $S_{11} = -2.4$ dB was achieved. A 0.2 dB difference in reflected power shows that the impedances (hence permittivities) of the two liquids are very similar.

Also, it is shown below that even for large changes in the reflection coefficient (due to large changes in load impedance), the reflected power is **NOT** markedly affected.

For a voltage reflection coefficient p' :

$$\text{where } p' = \frac{Z_1 - Z_0}{Z_1 + Z_0} \quad (36)$$

and Z_1 = Load impedance

Z_0 = Transmission line characteristic impedance

the **REFLECTED POWER** is p'^2 .

So for a 30 % change in the voltage reflection coefficient p' , the change in reflected power is only 9 %. Further, if Table III^(V) is examined, it is seen that the real impedance varies by approximately 10 Ω over an 80 °C temperature range.

The difference in reflection coefficient for two different loads (Z_{11} and Z_{12}) is : [See workings in Appendix A].

$$dp' = p'_{11} - p'_{12} = \frac{2 \cdot Z_0 \cdot (Z_{11} - Z_{12})}{(Z_0 + Z_{11}) \cdot (Z_0 + Z_{12})} \quad (37)$$

Thus, if a Z_0 (Transmission line characteristic impedance) of 200 Ω was used (purely a numerical example), then the change in voltage reflection coefficient will be :

$$dp' = 6.4 \%$$

For $Z_{11} = 42.5$ TABLE (IV)

$$Z_{12} = 52.3$$

Thus, the change in reflected power is:

$$(dp')^2 = 0.4 \%$$

This example serves to show that the single mode waveguide is insensitive to changes in the load impedance in the temperature range of interest.

Also, since S_{11} of milk changes so little when compared to that of water (this is to be expected since bulk of the milk volume is water - See Chapter 1), the impedance of the milk may be approximated to be that of water i.e.

$$Z_{\text{milk}} \approx Z_{\text{water}} \quad (38)$$

8. APPLICATOR DESIGN

8.1 Transmission line impedances and choice of heating mode

Figure (IX) (on the following page) is a diagram showing the components of the MMP transmission line.

The MMP uses a 500 W (2.45 GHz) magnetron which couples power (via a co-ax probe) into the **launch guide**. The microwaves then pass through a rectangular waveguide which has provision made for tuning screws (**matching screw waveguide**). The microwaves then pass through a **quarter-wave transformer** followed by a half-wavelength of cylindrical waveguide (**half-wavelength space**). The microwaves energy then couples into the **load** (milk/water).

The dimensions of the waveguides are chosen so as to facilitate impedance matching which results in optimal coupling of the microwave energy into the load (i.e. so there is minimal reflection off the load back towards the source).

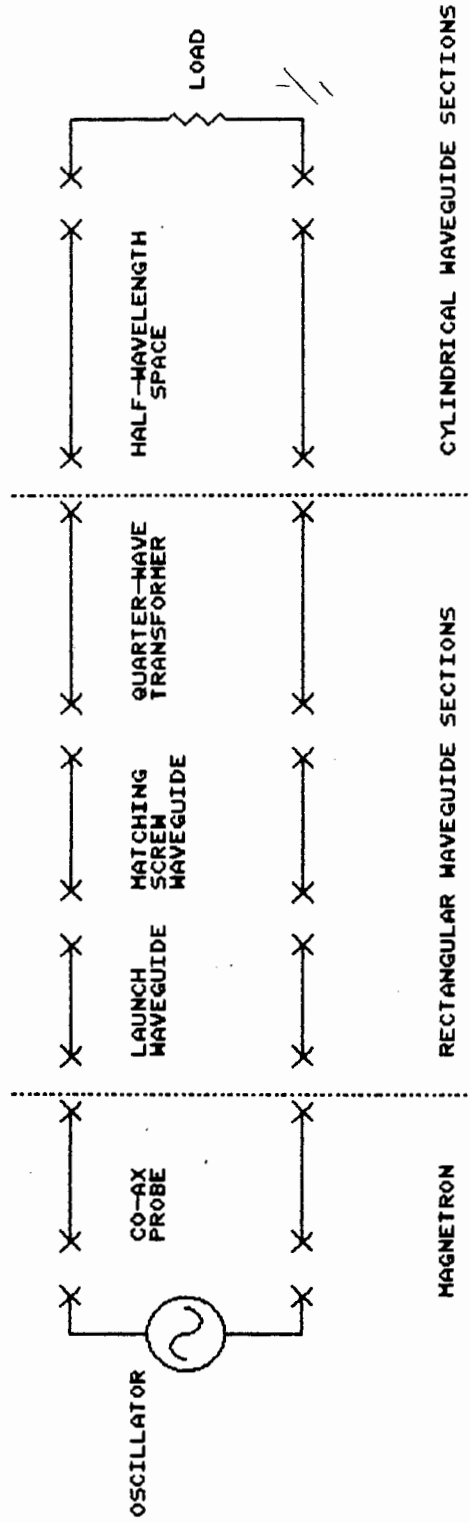


FIGURE (IX)

The cylindrical and rectangular waveguides have guide wavelengths and characteristic impedances associated with them. The wave equations, together with the guide wavelengths and characteristic impedances characterizing these waveguides are discussed in Appendix B.

In order to transfer energy uniformly into the milk, a suitable propagating mode for the circular waveguide must be chosen. The applicator must be designed to simply (i.e. extra waveguides with special tapers must be avoided) set up this mode.

It is best to design the waveguide so that only the dominant mode exists, as the energy in the higher order modes decay more rapidly [24]. Although all modes do exist simultaneously in a waveguide, only the dominant mode will propagate while the higher order modes decay (near the source or waveguide discontinuities).

In the cylindrical waveguide, two possibilities for uniform irradiation of the load exist. These are if energy in either the $TE_{1,1}$ or the $TE_{0,1}$ modes is incident on the milk / water.

Following are graphical representations of the electric and magnetic field distributions for the two modes. The TE_{11} mode is the fundamental mode which propagates in circular waveguides. The solid lines denote the electric field lines and the dotted lines denote the magnetic field lines.

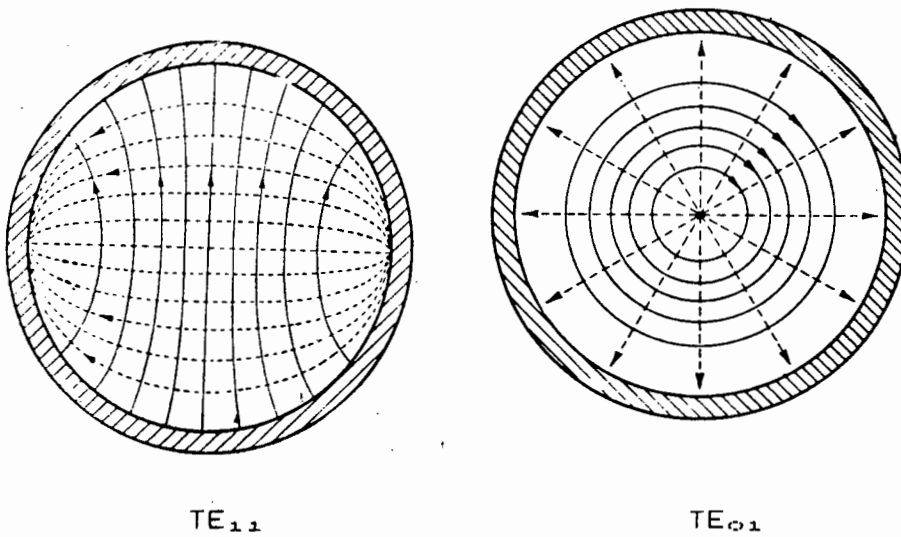


FIGURE (X)

For reasons discussed in section 8.2.2 a) of this chapter, the TE_{11} mode has been chosen to transfer energy towards the load (milk/water).

8.2 Waveguide choice and design

The following sections discuss the characteristics of the individual components which make up the transmission line.

8.2.1 Launch guide

The magnetron launches microwaves (TE_{10} mode - see FIGURE (XI)) into a rectangular waveguide (called the **launch guide**) by means of a coaxial line probe.

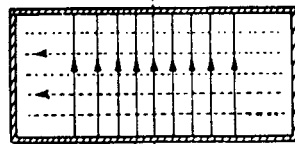


FIGURE (XI)

The guide dimensions are chosen to be the same as that for the launch guide of a microwave oven. The reason is as follows. The magnetron has a characteristic impedance which must be matched to that of the launch guide in order that the magnetron's transmitted power is **not** reflected back towards it. Since microwave power couples efficiently into standard microwave ovens, it is assumed that the launch guide dimensions are designed in order to facilitate a match between the magnetron and the launch guide.

The guide dimensions are set that only the dominant TE_{10} mode can propagate in the guide. See Chapter 11 for an accurate drawing of the launch guide.

Following is the determination of the guide wavelength
(L_{launch}) and the launch guide characteristic impedance
(Z_{launch}) in the launch guide :

The launch guide has dimensions a, b:

(see figure (XII) below)

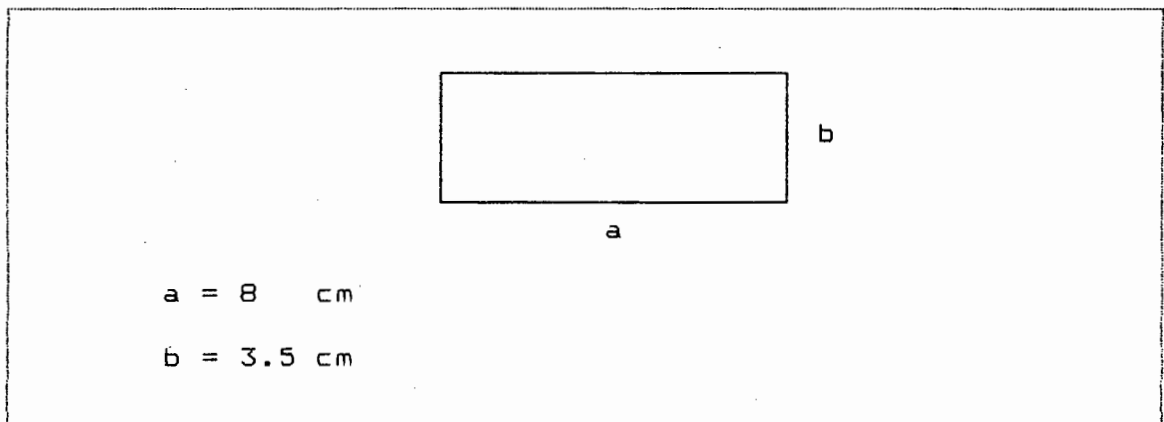


FIGURE (XII)

For $f = 2.45 \text{ GHz}$

$$L_0 = \frac{c}{f} = 12.2 \text{ cm} = \text{the free-space wavelength}$$

Where $c = 3 \times 10^{10} \text{ cms}^{-1}$

Also, $L_c = (2 \times a) = 16 \text{ cm}$

So the guide wavelength (L_{launch}) is, using the Equation (39) :

$$L_g = \frac{L_0}{\sqrt{1 - \left[\frac{L_0}{L_c} \right]^2}} \quad (39)$$

$$L_{\text{launch}} = L_g = 18.9 \text{ cm}$$

further, $\frac{L_g}{L_0} = 1.55 \text{ p.u.}$ (This result is used in Equation (40))

The guide characteristic impedance (Z_{launch}), using the Equation (40) below is :

$$Z_g = Z_0 \cdot \frac{b}{a} \cdot \frac{L_0}{L_g} \quad (40)$$

$$Z_{\text{launch}} = Z_g = 255.6 \, \Omega$$

8.2.2 Circular waveguide

The milk / water is housed in a cylindrical plastic container (PTFE). The container has dimensions (OD = 151 mm and ID = 147 mm). Assuming the milk has an impedance approximately equal to that of water (See section 7.3.2 Equation (38)), the impedance that is matched to is :

$$\begin{aligned} Z_{milk} &= 45.9 + j 2.04 \Omega \\ &\approx 46 \Omega \end{aligned}$$

Since impedances transfer (See Figure (XIII) on the following page) through a half guide wavelength (i.e. $L_g/2$) , a length of the circular waveguide has been left open (L_{space}) between the milk and the **quarter-wave transformer**. Another function of this half-wavelength is so that the TE_{11} mode can form in the circular waveguide after microwave energy passes through the **quarter-wave transformer** (towards the load).

The length of free space (between the **quarter-wave transformer** and the load) left in the circular waveguide is determined as follows :

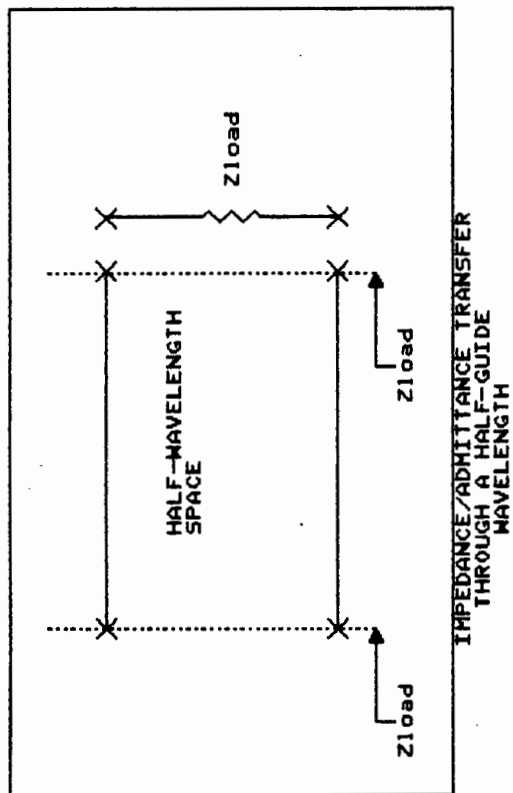


FIGURE (XIII)

First the cut-off wavelength (L_c) for a circular wavelength is determined using Equation (42) :

The cut-off wavelength (L_c) is determined from Equation (41) :

$$f_c = \frac{X'_{np}}{\pi \cdot D \cdot \sqrt{(\epsilon \cdot \mu)}} \quad (41)$$

where $D = 2 \cdot a$ = Diameter of circular waveguide

$$L_c = \frac{c}{f_c} = \frac{\pi \cdot D \cdot \sqrt{\epsilon_r}}{X'_{np}} \quad 3.41 a \sqrt{\epsilon_r} \quad (42)$$

since :

$$\frac{1}{\sqrt{(\epsilon \cdot \mu)}} = \frac{c}{\sqrt{(\epsilon_r \cdot \mu_r)}} \quad (43)$$

where:

$$c = \frac{1}{\sqrt{(\epsilon_0 \cdot \mu_0)}} \quad \text{and} \quad \mu_r = 1 \text{ for Dielectrics}$$

So, with $D = 152 \text{ mm}$, $\epsilon_r \approx 1$ (air)

$X'_{np} = 1.841$ See TABLE (VI) in APPENDIX B

($n = 1$, $p = 1$) since we are concerned with the TE_{11} mode.

$$L_c = 25.9 \text{ cm}$$

Thus with L_c in Equation (39)

$$L_{space} = \frac{L_0}{2} = 6.9 \text{ cm}$$

8.2.3 Transitions

A transition is needed to match the launch waveguide (a rectangular waveguide) to the cylindrical waveguide (which hold the milk).

a) Taper

If we wished to set up a TE_{01} mode (which can provide a uniform illumination of the load) on the circular waveguide, we would require a taper. The taper required would have to be specially constructed and would be made of a series of quarter-wavelength sections. However, a quarter-wavelength is of the order of 3.5 cm (if we assume that the guide wavelength under consideration is that for a circular waveguide). If say, 4 quarter-wavelength sections are used, then the transition would be about 14 cm. Apart from the practical difficulties involved in making such a taper, the length becomes impractical. Further, to ensure minimal reflections, far more than 4 quarter wavelength sections are needed to form the taper. It is for the above reasons that the TE_{01} mode is not used in the MMP.

b) Quarter-wave transformer

As a result of there being differences in the cross sections (hence impedance) of the rectangular launch waveguide and the circular waveguide, a quarter-wave transformer is used to match the two impedances to each other. Circuit (I) (on the following page) is the equivalent circuit of a quarter-wavelength transformer.

The junction effect (i.e. the phase of the reflected wave is altered) represented by (jB) however, only becomes significant at high frequencies when the waveguide dimensions become very small [24]. The frequency sensitivity of a single quarter-wavelength transformer is not very large [24].

The quarter-wavelength transformer characteristics and dimensions are as follows:

Since:

$$Z_{\text{launch}} = 255.6 \, \Omega$$

$$\text{and } Z_{\text{load}} \approx 46 \, \Omega$$

It follows from Equation (44) :

$$Z_{\frac{1}{4}} = \sqrt{ (Z_{\text{launch}} \cdot Z_{\text{load}}) } \quad (44)$$

[24]

$$\text{that } Z_{\frac{1}{4}} \approx \sqrt{ (255.6 \times 46) } \, \Omega$$

$$\text{i.e. } Z_{\frac{1}{4}} \approx 108.4 \, \Omega$$

If the waveguide dimension a is kept equal to 8 cm (this ensures that the guide wavelength L_g stays the same between the transmission line components), then from equation (40) we get :

$$b_{\frac{1}{4}} = a \cdot \frac{Z_{\frac{1}{4}}}{Z_0} \cdot \frac{L_0}{L_g} \quad (45)$$

$$\text{where } Z_0 = 120 \cdot \pi \cdot \Omega$$

From (45) we get $b_{\frac{1}{4}} = 1.48 \text{ cm}$

$$\approx 1.5 \text{ cm.}$$

The length of the transformer using Equation (39) is :

$$L_{\text{transformer}} = \frac{L_{\text{launch}}}{4} = 4.73 \text{ cm}$$

X

8.3 Stub tuning

The **Quarter-wave transformer** is used for **resistive matching**. Due to changes in cross sectional area in the waveguides and due to transitions from air to dielectrics (milk, water and PTFE), there is some **reactive mismatch**.

Tuning screws can be inserted into the waveguide to provide a **variable susceptance** to cancel out the reactive mismatch. The screws must be fitted in a close fitting sleeve or be securely locked at the point of insertion into the waveguide [24]. When the screws penetrate the waveguide, currents flow along the screw. Thus, the sleeve or screw threads must provide a good electrical contact with the waveguide. Generally, the tuning screws are only useful to match out small standing-wave ratios [24]. Thus, the design of the other applicator components must ensure that only a small VSWR exists (without the tuning screws).

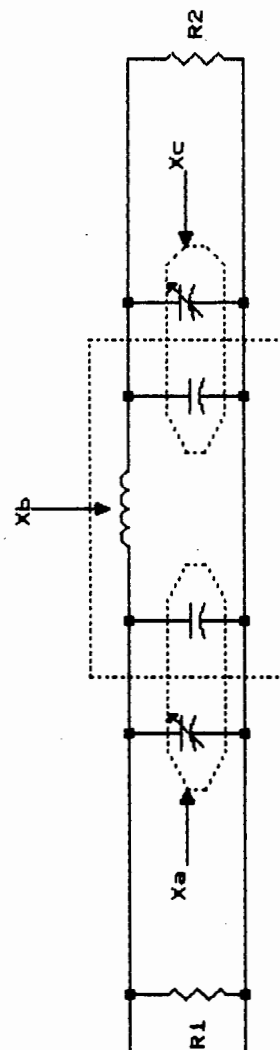


The operation of the stub tuner can be understood as follows. The explanation is based on the operation of a double-stub tuner. The equivalent circuit (Circuit (II)) is shown on the following page [25].

Consider the dotted enclosure to be a lossless π section of length l . X_A and X_C must be negative (capacitive). It is possible to match any R_1 and R_2 if X_B is less than $\sqrt{(R_1 \cdot R_2)}$. But :

$$X_B = Z_0 \cdot \sin \beta l \quad [24]$$

So, to make X_B small, it is necessary to make $l = 0$ or an integral multiple of $L_0/2$. It turns out that by making l these values, the required values of X_A and X_C become very nearly zero. Thus, there are large, unwanted circulating currents. The length l is best chosen between $L_0/8$ and $3L_0/8$ or $5L_0/8$ and $7L_0/8$ [24].



CIRCUIT REPRESENTATION OF A DOUBLE-STUB TUNER

CIRCUIT (II)

This model can be extended to that of a triple-stub unit if one considers the triple-stub unit to be two double stubs in parallel. The first double-stub matches R_1 to **any** suitably high resistance, and the second double-stub matches this high resistance the low resistance R_2 . It follows that with a triple-stub tuner, **any** two impedances can be matched to each other.

8.4 Summary of Applicator Characteristics

The applicator consists of a magnetron launching power into a launch waveguide. As a result of the possibility of some reactive mismatch, a length of tuning-screw waveguide is then added. By means of a Quarter-wave transformer, the load impedance is matched to the launch waveguide impedance. The Quarter-wave transformer matches out the resistive mismatch. The tuning screws cater for the reactive mismatch.

Waveguide	Impedance	Dimensions			
		a	b	D	Length
Name	Ω	mm	mm	mm	mm
Launch	255.6	80	35	N/A	80
Tuning-screw	255.6 + jVAR	80	35	N/A	VAR
$\frac{1}{4}$ - Wave Tx	108.4	80	15	N/A	47
$\frac{1}{2}$ - Wave Space	427.4	N/A	N/A	151	69
Load	46	N/A	N/A	147	VAR

VAR = Variable

N/A = Not Applicable

9. TEMPERATURE MEASUREMENT

9.1 Temperature Sensor choice

Temperature can be measured in a number of ways. Amongst these are the use of Thermocouples (TC's), Resistance Temperature Detectors (RTD's), Thermistors, Gas Filled Thermal Systems and Radiation pyrometers.

The sensor must have certain qualities to ensure accurate temperature measurement and control. These are :

- 1: The temperature sensor must have good thermal linkage with it's surroundings.
- 2: Heat flow along the connecting wires is unwanted and should be minimized (this is done by using teflon-insulated wire. Teflon is a **good** heat insulator).
- 3: Temperature gradients close to the sensor should be minimized (this is achieved by providing enough immersion depth and using a support with a high axial thermal resistance e.g. thin stainless steel).

- 4: The sensor must not affect the temperature being measured. This is minimized if temperature measurement is **not** done at the surface of the milk and the sensor does **not** self-heat (in this case due to the current flowing through the sensor or due to the current induced in the surface of the stainless steel by the microwaves).
- 5: The sensor should have a response time of less than that of the liquid it is measuring.

Three temperature sensors have been considered for the MMP. These include the TC, RTD and the Thermistor. The Gas Filled Thermal Systems have been **excluded** because of their cost and the Radiation pyrometers because their main use is for the measurement of surface temperature [28].

Following is a table summarizing the characteristics of the different sensors [28]:

Characteristic	Platinum RTD	Thermistor	TC
Range [°C]	-250 to 650	-195 to 450	-200 to 1700
Typ. Accuracy	$\approx 0.1^{\circ}\text{C}$ @ 0°C $\approx 1.3^{\circ}\text{C}$ @ 650°C	$\approx 0.2^{\circ}\text{C}$ @ 25°C $\approx 1.0^{\circ}\text{C}$ @ 150°C	$\approx 2.2^{\circ}\text{C}$ @ 0°C $\approx 9.4^{\circ}\text{C}$ @ 1250°C
Drift	$< 0.1^{\circ}\text{C}/\text{Yr}$	$< 0.11^{\circ}\text{C}/\text{Yr}$	$< 5^{\circ}\text{C}/\text{Yr}$
63 % Response Time [Sec]	2.2	1	1
Linearity	Excellent	Poor	Good
Sensor Size	Smaller than TC	Smallest	Larger than Thermistor
Advantages	Best Accuracy & Stability over wide spans	Greatest sensitivity (Small spans)	Widest Span, Highest Temp. Capability
Disadvantages	Not as rugged as other sensors, Subject to self-heating errors	Narrowest span, Subject to self-heating errors	Most Drift, Lower signal than RTD's, Requires reference junction compensation

TABLE (V)

From Table (V), it can be seen that the RTD achieves the best temperature accuracy and maintains the best measuring stability. Further, the best accuracy that can be achieved by a TC is of the order of 2.2 °C. Thus, the TC is not suitable for the MMP (the MMP requires a temperature measurement accuracy of better than 1°C). The use of a thermistor for the MMP has been **discounted** because of its **poor linearity** (linearizing circuitry would be required).

A platinum element RTD called a Pt100 is to be used in the MMP. It has the following characteristics [27]:

- 1: A time constant of less than 2.2 seconds.
- 2: An accuracy of $\pm 0.1 \Omega$ at 0 °C.
- 3: A reproducibility of $\pm 0.1 \%$ of resistance for a 100 Ω element.
- 4: It can be attached to a (4-20 mA) amplifier.
- 5: It has a Superior Corrosion Resistance with a low carbon 316 ST/ST (Stainless Steel) sheath.
- 6: The sheath can also be sharply bent with no change in performance. This is important in the construction of the MMP.
- 7: The Pt100 has an approximately linear Resistance vs Temperature characteristic for the temperature range (0 - 100) °C.

The RTD will be entered into the milk from the top of the milk housing (a PTFE container) and it will lie **perpendicular** to the electric field so as to:

- 1: Not perturb the electric field,
- 2: Not be self-heated due to microwave induced currents on the surface of the stainless steel.

Tests performed in [26] show that the convection mechanism of heat transfer is efficient enough to ensure uniform heat distribution through the milk housing. The tests illustrate that as a result of internal heating and convection, the temperature rises uniformly throughout the milk.

10. ELECTRICAL/ELECTRONIC CIRCUITRY

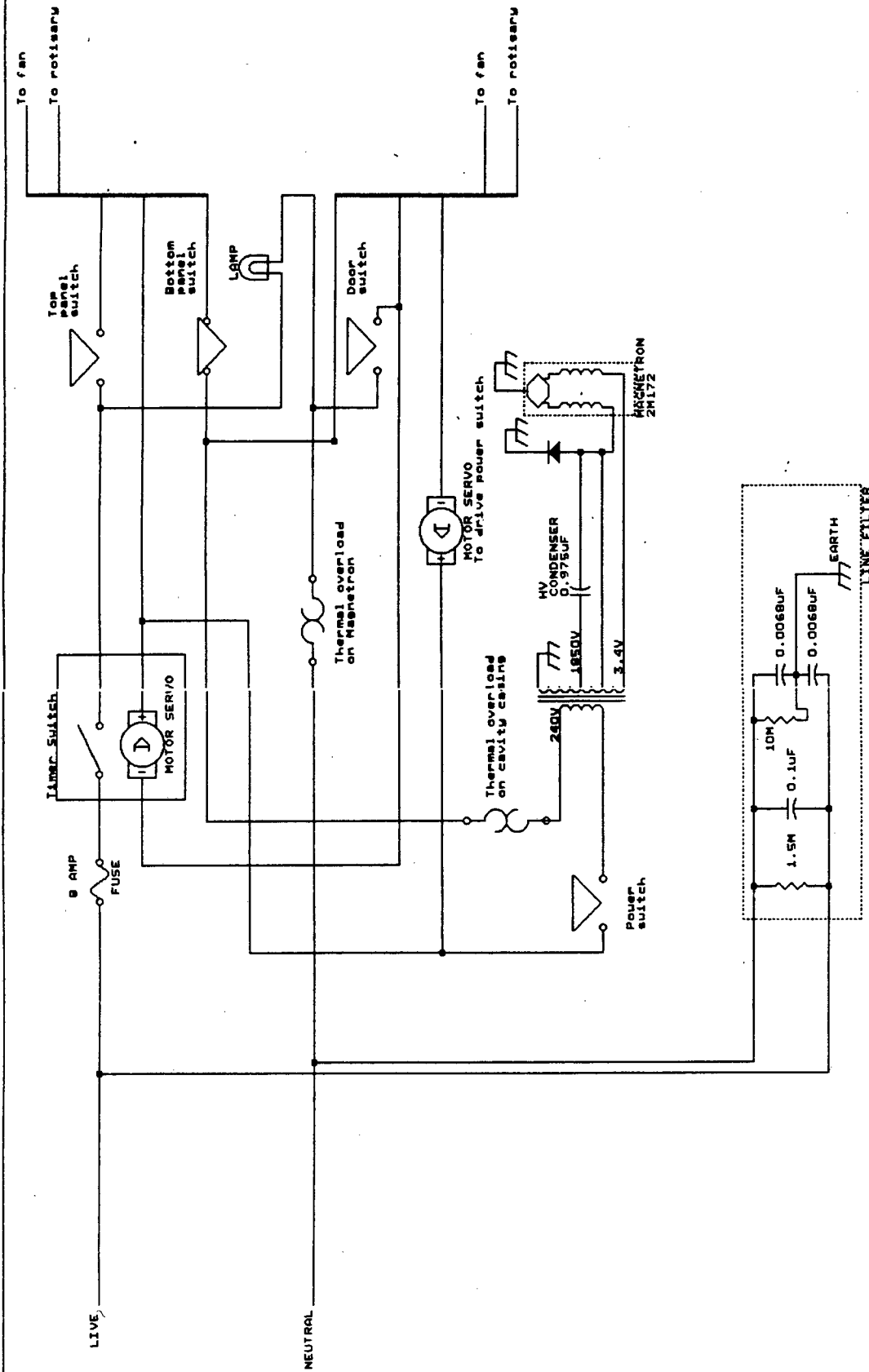
This chapter discusses the circuitry of a 500 Watt AIM microwave oven, showing important aspects of design which have to be included in the MMP. It then discusses the Electrical/Electronic circuitry requirements of the MMP. Possible temperature control options are then discussed, followed by a description of the Timing and Interlock and Temperature Measurement circuitry used in the MMP. Then, there is a report on research done in an effort to implement Proportional temperature control. A complete circuit diagram is shown in APPENDIX E.

10.1 Microwave Oven circuitry

To understand the electronic circuitry required (in terms of safety), the circuitry of a standard microwave oven was examined. Information concerning the general workings of a microwave oven was determined from studying the circuit diagram.

This section discusses the some important safety features implemented in the oven, the power supply to the magnetron and the cooling of the magnetron.

Circuit (III) (following page) shows the circuitry of a 500 Watt AIM microwave oven.



CIRCUIT (III)

AIM 500W MICROWAVE OVEN CIRCUITRY

10.1.1 Safety features

It is most important to note the safety feature employed in the interlock system. There are two interlock switches in the door (**Top panel switch and Bottom panel switch**), one N.O. (Normally open) and one N.C. (Normally Closed). As the door is opened, two events occur simultaneously. These are that the A.C. power is removed (this occurs when the N.C. switch opens) and the primary of the Magnetron transformer is shorted (this occurs when the N.O. switch closes). The result is that stored electrical energy (in the doubling capacitor) and the stored magnetic energy (in the transformer) are dissipated immediately (thus, the magnetron stops emitting power **immediately**).

Thermal cut-out switches secured to the **cavity wall** and **magnetron** open if the either the cavity or magnetron overheats.

An RC line filter is employed to prevent the surge currents drawn by the magnetron's transformer from adversely affecting the supply voltage. This is in accordance with the safety requirements that the device may not affect the A.C. supply line that may be supplying power to a voltage sensitive device nearby.

10.1.2 Power Supply and Control

Power control is achieved by using timer and power selection switches. Power control is achieved through time cycling. A duty period of typically 10 seconds is used [15]. When 50 % power is selected on the power selection switch, the magnetron is switched ON for 5 seconds and OFF for 5 seconds.

Power to the magnetron is supplied via the magnetron transformer. The supply voltage of 220 volts A.C. is stepped up to approximately 1850 volts. This voltage is then doubled and rectified (\approx 3700 Volts D.C.) by means of a capacitor/diode doubler. This voltage is then applied across the Anode/Cathode of the magnetron. Further, a supply of 3.4 VAC is supplied to the heating element of the cathode.

10.1.3 Magnetron Cooling

The magnetron is heated up during its operation as a result of cathode heating and as a result of reflected power. Reflected power results in an electric field (hence surface currents) across the metal launch probe of the magnetron. This necessitates the use of a blower fan to pass cool air over the cooling fins of the magnetron.

The following solutions exist for the above needs :

1. A programmable controller can be bought which can fulfill the above needs i.e. **BOTH** programs can be fulfilled by ONE controller (in terms of temperature control and timing).
2. Two simpler controllers can be bought (without timing facilities) and analog timing circuitry can be implemented to ensure the temperatures are maintained for the correct time.
3. Two separate proportional-controllers can be built and used with analog timing circuitry.

In all three cases above, either ON/OFF control or Proportional control can be implemented. Unfortunately, a dead-time exists if ON/OFF control is used (when the OFF time is in excess of approximately 1 second, the cathode must be reheated during the ON time). Also, the use of high switching speeds by an ON/OFF controller can lead to large surge currents passing through the magnetron transformer, causing overheating of the transformer. This problem can be obviated if a separate transformer is used to supply the 3.4 VAC to the CATHODE heating element. This transformer must have a Breakdown Voltage in excess of 4000 Volts.

Option 1 has been discounted because Programmable Controllers (to fulfill the needs for the MMP) cost in excess of R3500.

Option 2 is also expensive because these controllers cost in excess of R500 each.

Circuitry has been designed which tests the feasibility of using Option 3. This research is discussed in Section 10.5.

10.4 Milk unit circuitry

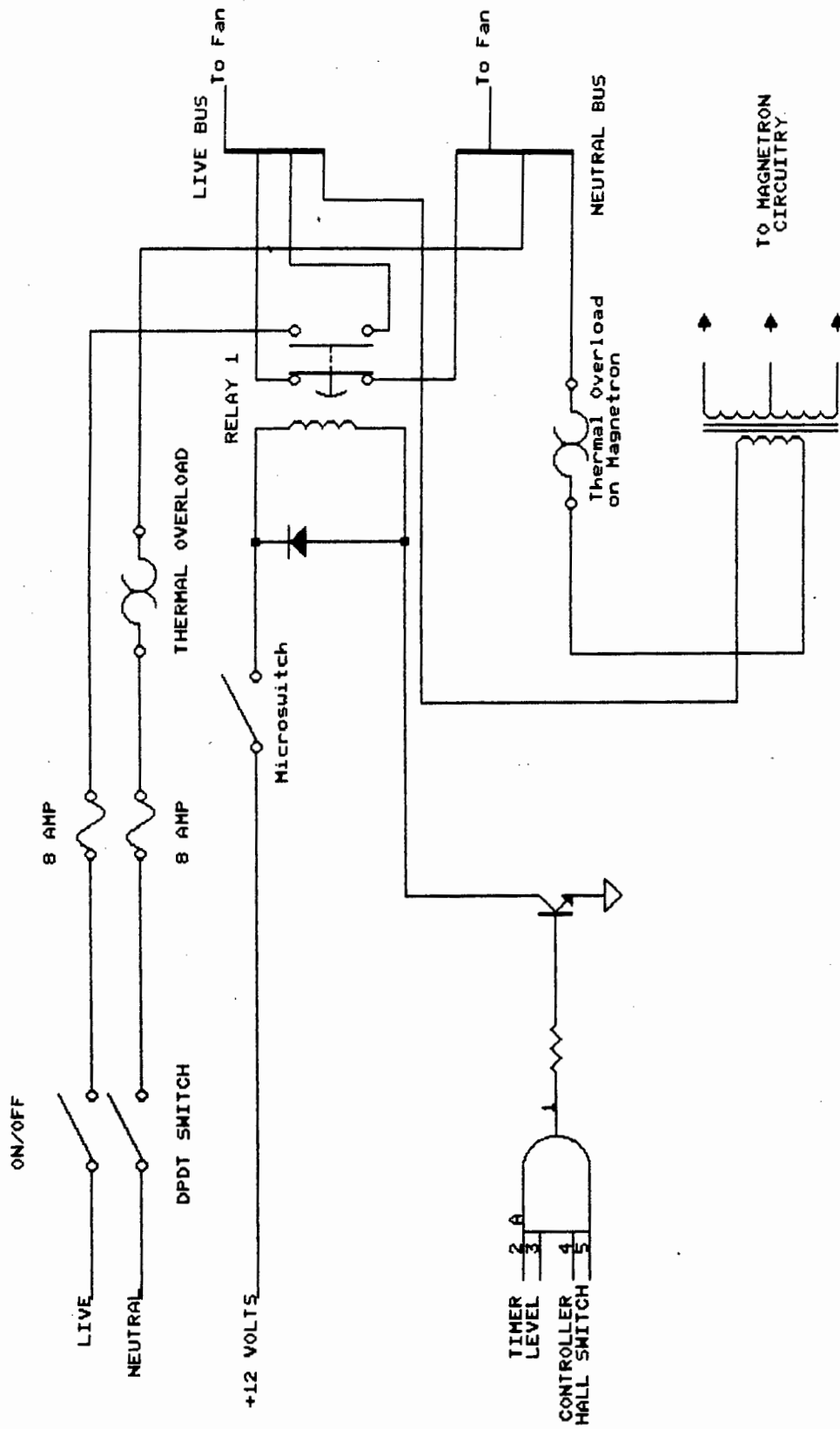
This section discusses the Timing electronics which is needed to maintain the temperature of the breast milk within (56-57.5) °C for 33 min and the temperature of water at 100 °C for approximately 1.5 min. It also discusses the interlock circuitry required to ensure safety of the MMP user.

10.4.1 Interlock circuitry

If Circuit (IV) on the following page is examined, the operation of the MMP becomes clear. As long as the signals TIMER, LEVEL, CONTROLLER and HALL SWITCH are ACTIVE, and the MICROSWITCH is closed, then the magnetron can be activated by the temperature controller.

The electronic interlocks signals are TIMER, LEVEL, HALL SWITCH and the mechanical interlock is the MICROSWITCH.

In ON/OFF control the power supply voltage is kept constant and the CONTROLLER signal is switched ON and OFF under the influence of the controller. In Proportional control, the CONTROLLER signal is kept ACTIVE and the power supply voltage is altered under the influence of the controller.



BASIC CIRCUITRY

CIRCUIT (IV)

The interlocks used in the MMP are described as follows :

- 1:TIMER : This signal is ACTIVE when the load is being brought up to temperature and when the temperature is being maintained within the required temperature band e.g. (56-57.5) °C for 33 min. See Section 10.4.2 for a more detailed description of this interlocks action.
- 2:LEVEL : To ensure that there is no possibility that the load can be 'BOILED OFF' due to malfunction of the temperature controller, a level sensor is implemented which deactivates the magnetron when the level of the liquid being heated is below a certain level. This interlock prevents the possible complete reflection of power back to the magnetron and prevents the possibility of excess leakage radiation.

3:HALL SWITCH: To gain an understanding of the Hall Switch interlock, Figure (XVI) must be examined. In order that there is no leakage of liquid into the MMP housing, the magnetically operated Hall Switch is completely isolated from the outside of the Transformer and Magnetron Housing. As soon as the lid of the PTFE container is lifted, the Hall Switch is **deactivated** and the Magnetron is deactivated.

4:MICROSWITCH: To see the position of this mechanical interlock, Figure (XVI) must be examined. As a **fail-safe** interlock, this interlock ensures user safety (in the event of electronic circuitry malfunction).

The circuitry for the TIMING interlock is explained in Section 10.4.2.

The circuitry for the LEVEL and HALL SWITCH interlocks is explained in this section.

LEVEL circuitry

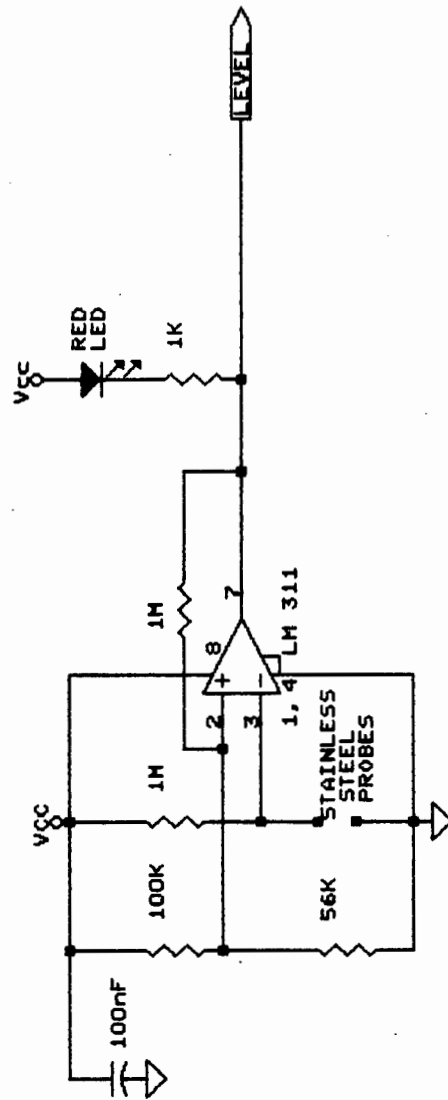
CIRCUIT (V) (following page) shows the Level Sensor circuitry.

The level sensor makes use of stainless steel probes which are placed into the liquid (milk/water). See Figure (XVI). The sensor makes use of an LM311 comparitor (open collector). When there is a conduction path between the probes, PIN 3 is pulled low, PIN 7 goes HIGH (thus LED is OFF) and the LEVEL signal is ACTIVE. This means the LEVEL Interlock is ACTIVE and, if all of the other interlocks are ACTIVE, then the magnetron can be activated. When there is no conduction path between the probes, PIN 3 is pulled HIGH, PIN 7 goes LOW (thus LED is ON) and the LEVEL signal is DEACTIVATED. The magnetron cannot be activated as long as the LEVEL signal is DEACTIVATED.

There is feedback between PIN 7 and PIN 2 to create hysteresis (thus insensitivity to switching noise). The analysis of the hysteresis voltage is given in APPENDIX C.

In this circuit, the hysteresis voltage is :

$$V_{hyst} = 35 \text{ mVolts}$$



LEVEL SENSOR

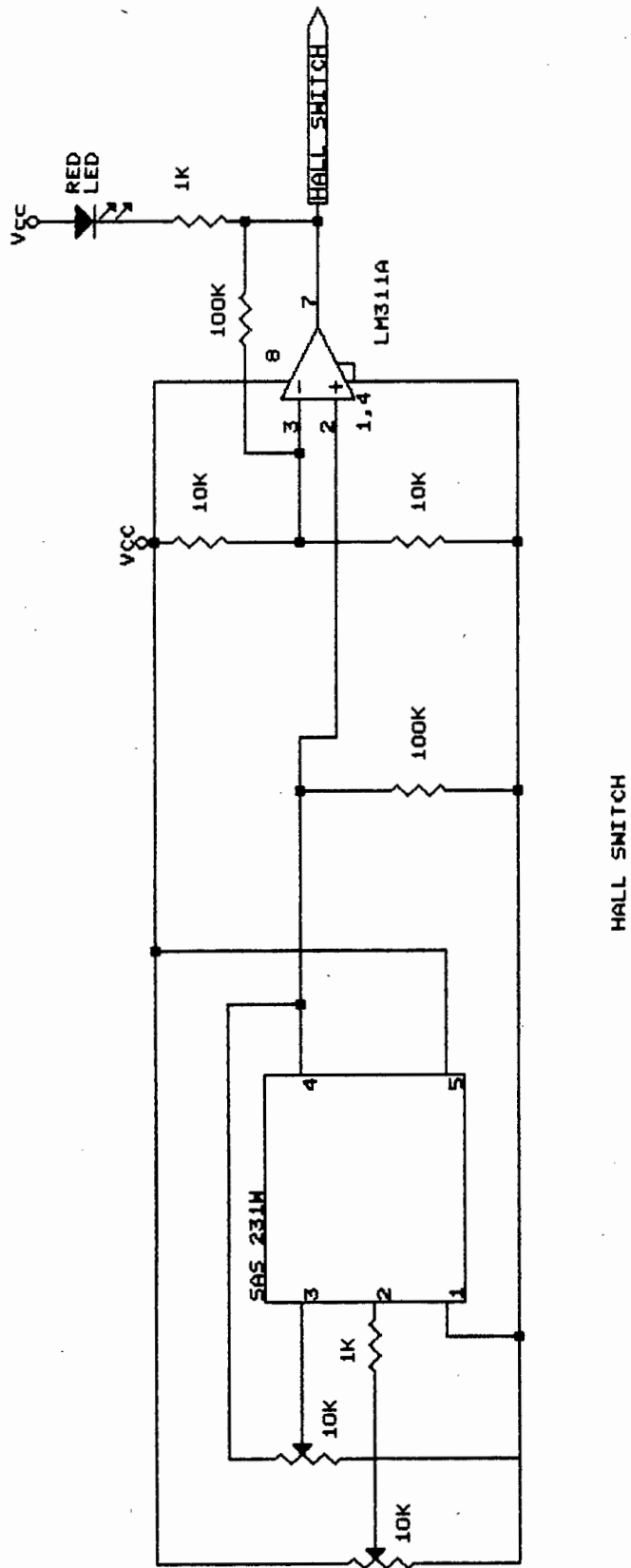
CIRCUIT (V)

HALL SWITCH circuitry

CIRCUIT (VI) (following page) shows the Hall Switch circuitry.

The sensor makes use of an LM311 comparator (open collector) and a Hall switch called the SAS231W. When a magnetic flux passes through the SAS231W microchip, PIN 4 (SAS231W) goes HIGH. PIN 7 (LM 311) goes HIGH (thus LED is OFF) and the HALL SWITCH signal is ACTIVE. When there is no magnetic flux passing through the SAS231W microchip, PIN 4 (SAS231W) goes LOW. PIN 7 (LM 311) goes LOW (thus LED is ON) and the HALL SWITCH signal is DEACTIVATED. (This occurs when the LID of the PTFE container is removed). When the HALL SWITCH Interlock is ACTIVE and, if all of the other interlocks are ACTIVE, then the magnetron can be activated.

There is feedback between PIN 7 and PIN 3 to create hysteresis (thus insensitivity to switching noise).



CIRCUIT (VI)

10.4.2 Timing circuitry

The timing circuitry has to fulfill the following functions. It must ensure the temperature of the breast milk is maintained in the temperature range (56-57.5) °C for 33 min. The same circuitry must ensure the PTFE container is sterilized with water for 1.5 minutes. Should the container be opened, the timer must be INHIBITED. The timing should only commence again once the PTFE container has been closed and the required temperature has been reached and maintained.

The TIMER signal must be ACTIVE when the load is being brought up to a temperature 100 °C for container sterilization or (56-57.5) °C for milk sterilization. It must also be ACTIVE when the temperature is being maintained at the required temperature.

From the FIGURE (XIV), the operation of the timing circuitry CIRCUIT (VII) can be understood.

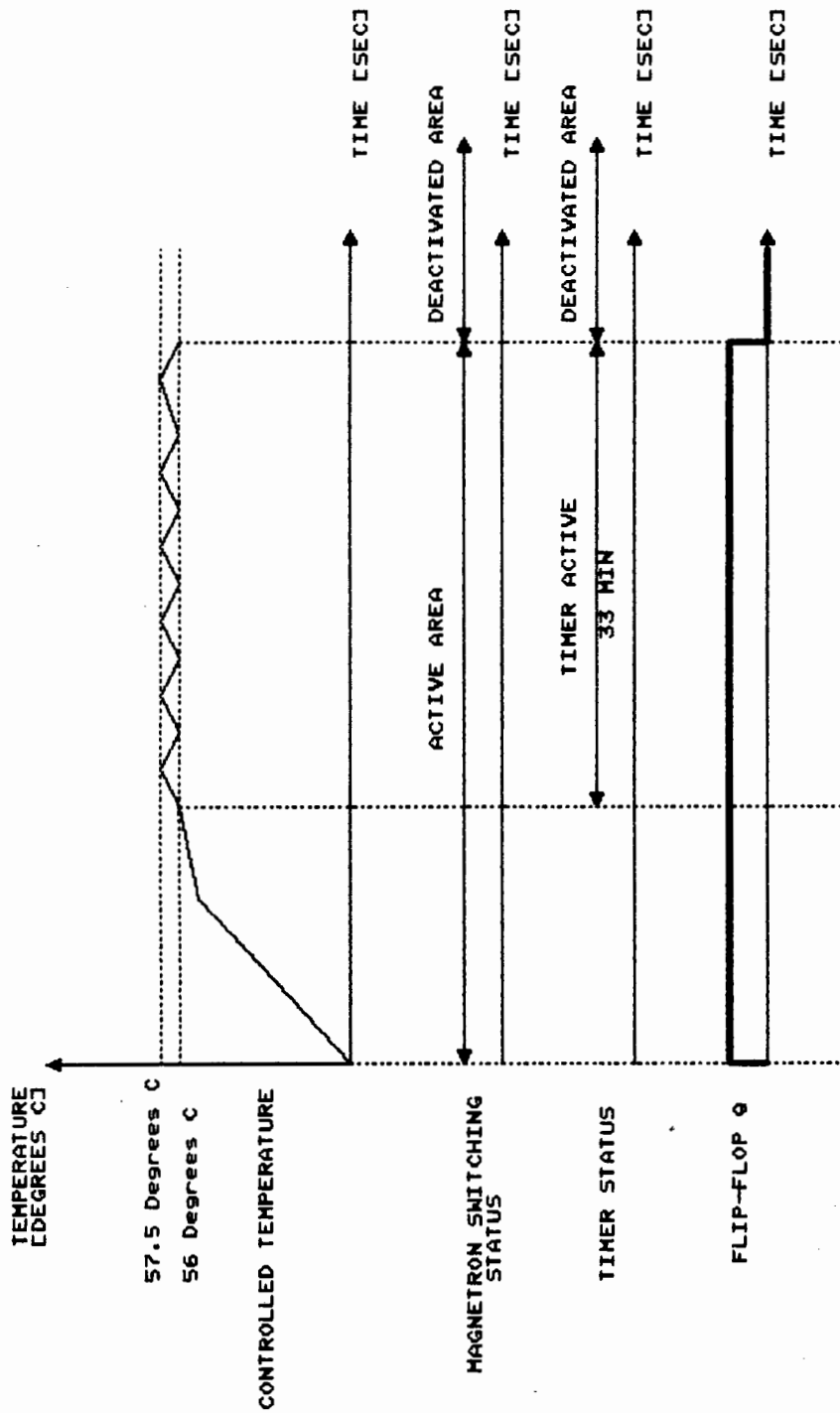
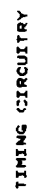


FIGURE (XIV)



The magnetron must be allowed to be activated (by the controller) as indicated in the ACTIVE area (See MAGNETRON SWITCHING STATUS - FIGURE (XIV)) . To ensure that this can occur, a flip-flop (4013 B) in CIRCUIT (VII) ensures the TIMER signal remains ACTIVE throughout the magnetron's ACTIVE area. As soon as the 4541's Q (CMOS timing IC) goes LOW, the flip-flop (4013 B) is triggered and its Q goes LOW. Thus, once the 4541's Q goes LOW (after it has finished timing), the TIMER signal remains LOW and the MAGNETRON is deactivated.

The comparator window is used to ensure that the timer is only activated when the measured temperature is within (56-57.5) °C (for milk sterilization). Another comparator is used to ensure that the timer is only activated when the measured temperature is above 98 °C (for sterilization).

The DG303A CMOS electronic switch has two functions :

- 1: It selects the timing mode (whether the time is 33 min. or 1.5 min.) for the CMOS 4541 timing IC.
- 2: It allows the ACTIVATE TIMER signal (CIRCUIT (VII).) to inhibit the timer if either the microswitch is not closed or if the temperature is not at its correct level (See FIGURE (XIV) - TIMER STATUS).

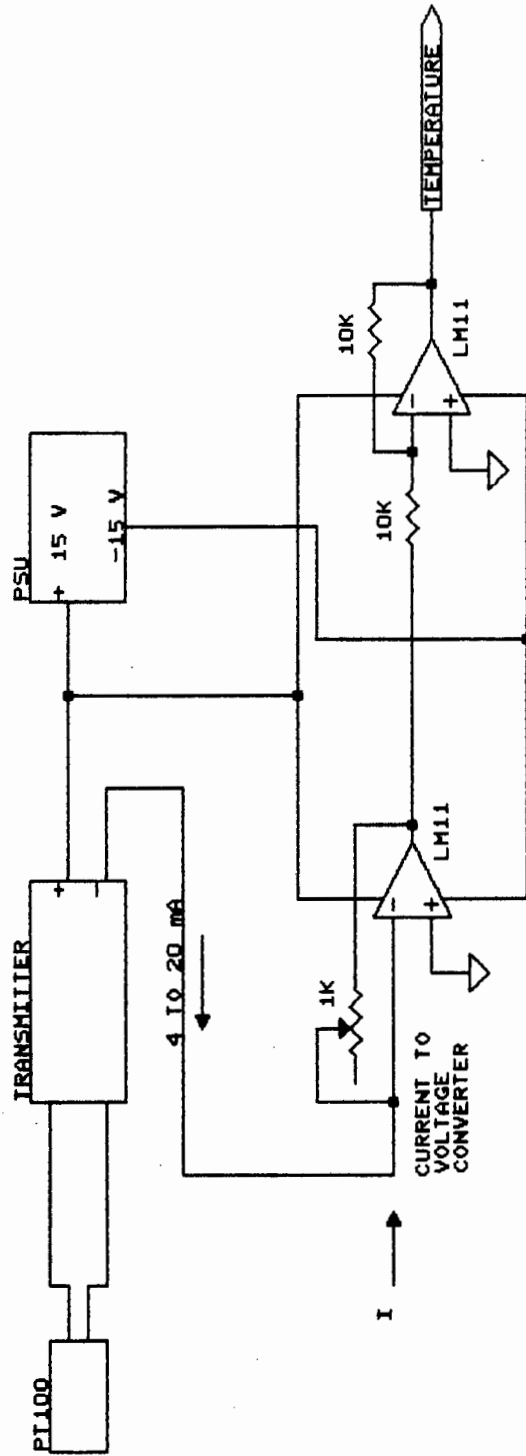
The particulars concerning component selection for the CD 4541 are discussed in APPENDIX D.

10.4.3 Temperature measurement circuitry

The Pt100 is connected in the configuration shown in Circuit (VIII) (following page).

A sensor current of approximately 0.6 mA is passed by the "HOCKEY PUCK" RTC transmitter through the Pt100. The output current of the transmitter is 4-20 mA. The supply voltage to the transmitter is 15 V. The output current is insensitive to variations in supply voltage (i.e. 0.001% of SPAN/V). The total error is low (0.2% of the span { in this case the span is 100 °C }). The transmitter has RFI and reverse polarity (PSU) protection.

The output current is fed into a precision , low drift, low offset operational amplifier (the LM 11). The OPAMP operates as a CURRENT-TO-VOLTAGE CONVERTER. The output voltage of the first OPAMP is then inverted by second LM11. The CURRENT-TO-VOLTAGE CONVERTER has a variable resistance in its feedback path. This resistance is adjusted until 20 mA (100 °C) from the transmitter gives an output of 10 V at TEMPERATURE (See Circuit (VIII)). This signal is used by the Timing-Interlock-Circuitry and the Temperature-Control-Circuitry.



CIRCUIT (VIII)

NOTES :

1. 20mA EQUIV. 100 DEGREES C
2. $V_o = -I.R$
3. For $R = 680 \text{ Ohms}$, $V_o (\text{max}) = -13.6 \text{ Volts}$
4. POT IS ADJUSTED TILL 20mA IS EQUIV. 10 V (@ TEMPERATURE)

TEMPERATURE MEASUREMENT CIRCUITRY

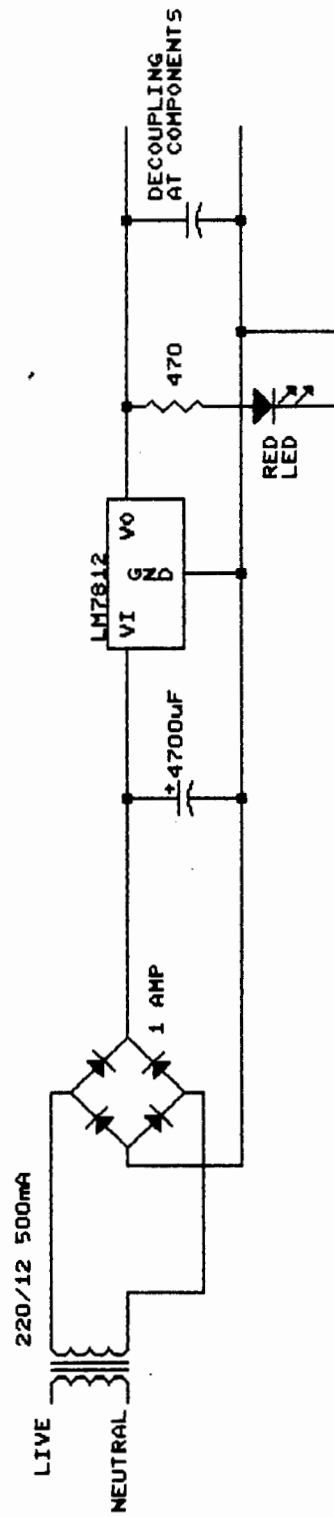
10.4.4 MMP Power circuitry

There are two power circuits. These are the electronic power supply (CIRCUIT (IX)) and the electrical power supply (CIRCUIT (X)).

By examining CIRCUIT (X), it is evident that an RC line filter (the same as in a 500 W AIM MICROWAVE OVEN) is used. The magnetron's power supply is the same as that for the 500 W AIM MICROWAVE OVEN. A Thermal overload switch is placed on the magnetron in the event that the magnetron overheats. A DP DT (Double Pole Double Throw) switch is used on the supply input to provide added electrical protection. As an added safety precaution, both the LIVE and NEUTRAL supplies are fused.

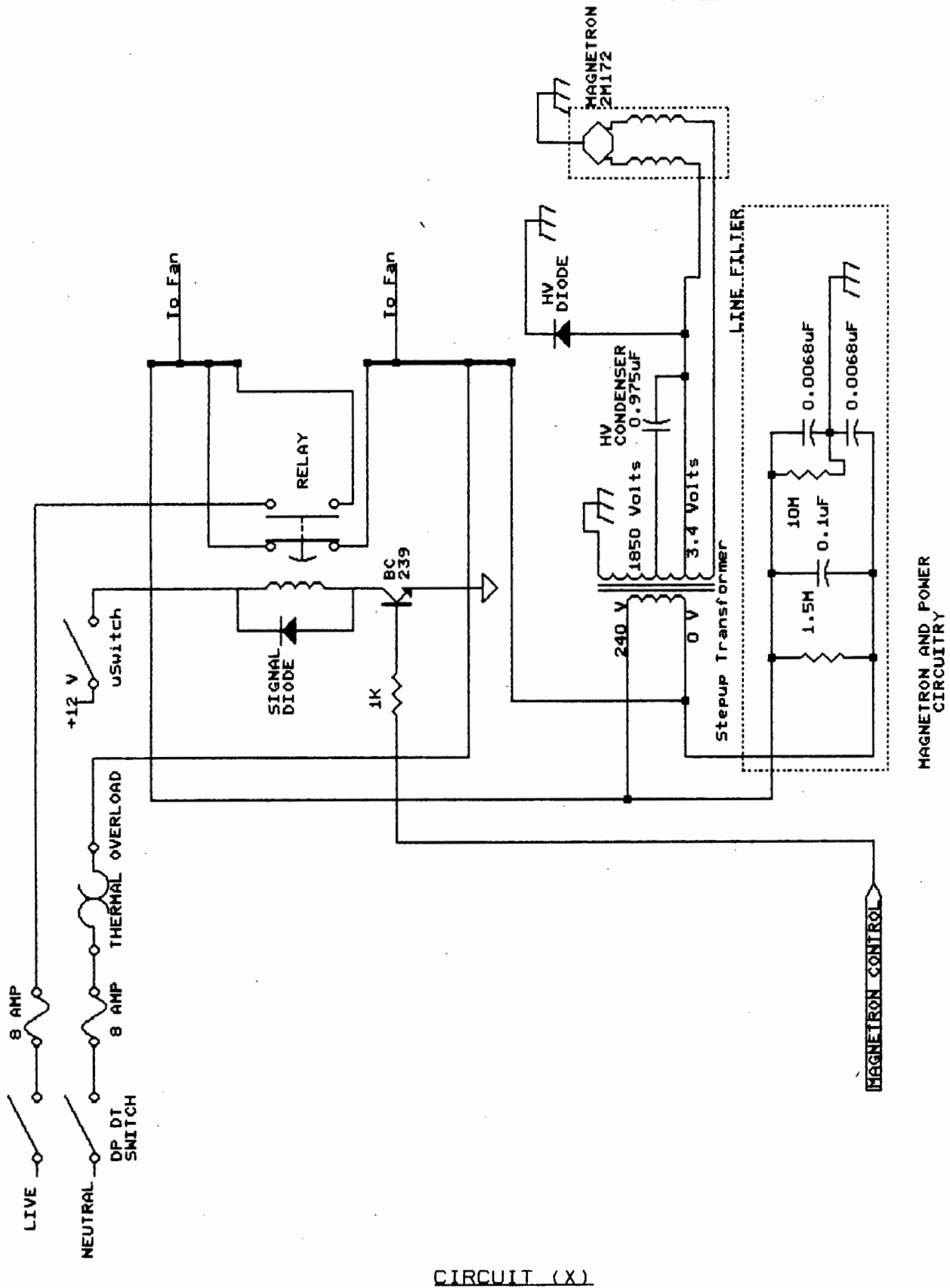
A 12 VDC , 16 AMP relay controls the supply of power to the magnetron (under the influence of the MICROSWITCH and the MAGNETRON CONTROL signal (composed of the TIMER, LEVEL, CONTROLLER and HALL SWITCH signals)). The relay controls both a N.O. and an N.C. contact. In the event that either the MICROSWITCH opens or the MAGNETRON CONTROL signal is DEACTIVATED, the mains supply is removed and the primary of the magnetron-transformer is shorted so that stored magnetic and electric energy is rapidly dissipated (manifested as heating of the primary and secondary windings).

The **electronic** power supply circuit (CIRCUIT (IX)) allows 220 VAC to be full-wave rectified, smoothed and then regulated to supply a steady 12 VDC to the electronic circuitry.



CIRCUIT (IX)

POWER SUPPLY CIRCUITRY



10.5 Power control

As discussed in Section 10.3, either **ON/OFF control** or **Proportional control** can be used for power control. The cheaper method is **Proportional control**. This chapter discusses research done into this alternative means of power control. An alteration of the output power has been achieved if the A.C. supply voltage is varied [30].

10.5.1 Variac

Tests were performed by altering the supply voltage to a standard microwave oven by means of a variac. The aim was to see how reduced mains input voltage affects the output power of the magnetron.

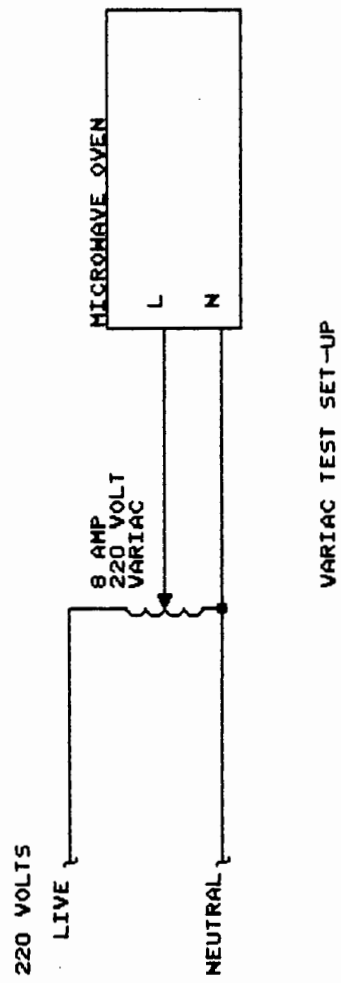
Circuit (XI) (following page) illustrates the experimental set-up.

The following tests were performed. A variable supply voltage was applied to a NATIONAL 700 W MICROWAVE OVEN (with rotisary) using an 8 Amp, 220 Volt Variac. The test involved heating a 300 ml water load for 90 seconds with the temperature being the dependent variable and the supply voltage to the magnetron being the independent variable. In each case, the ambient temperature (T_1 = initial temperature) of the water was $T_1 \approx 19^\circ\text{C}$. The load was heated for 90 seconds in each case. Temperature measurement was done using a thermometer after the load had been stirred (to ensure uniform temperature distribution throughout the load).

The results are tabulated in Table (VI):

INPUT VOLTAGE	T_{final}	dT	POWER
RMS A.C.	$^\circ\text{C}$	$^\circ\text{C}$	Watts
150	No Change	0	0
160	21	2	28
170	27	8	112
180	43	24	336
190	56	37	518
200	61	42	588
210	62	43	602
220	63	44	616

TABLE (VI)

CIRCUIT (XI)

The power absorbed by the load is determined using the Equation (17) :

$$P = \frac{d\theta}{dt} = m \cdot C_p \cdot \frac{dT}{dt} \quad (17)$$

Where $m = 300 \text{ grams} \approx 0.3 \text{ litre}$

$C_p = 4.2 \text{ J } ^\circ\text{C}^{-1} \cdot \text{g}^{-1}$

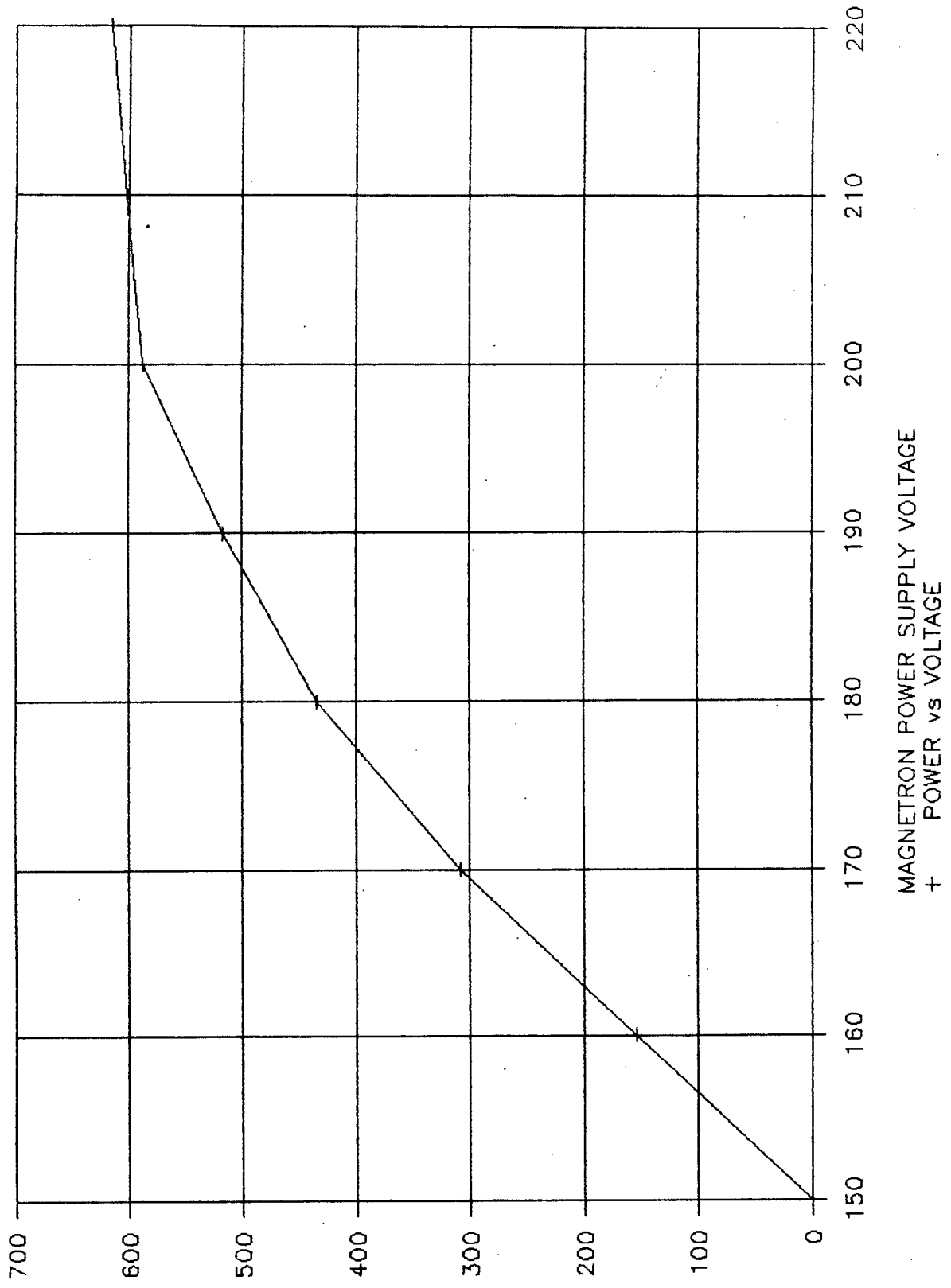
$dt = 90 \text{ sec.}$

Graph (I) on the following page shows the Power vs Voltage relationship.

As can be seen, there is linear relationship (in the (150 to 200 Volt) supply region) between the power output (assuming all of the energy supplied by the magnetron is maintained in the load) of the magnetron and the supply voltage to the magnetron .

POWER VS VOLTAGE

POWER IS ABSORBED BY 300mi LOAD



POWER

GRAPH (1)

MAGNETRON POWER SUPPLY VOLTAGE
+
POWER vs VOLTAGE

10.5.2 Integral-Cycle-Control

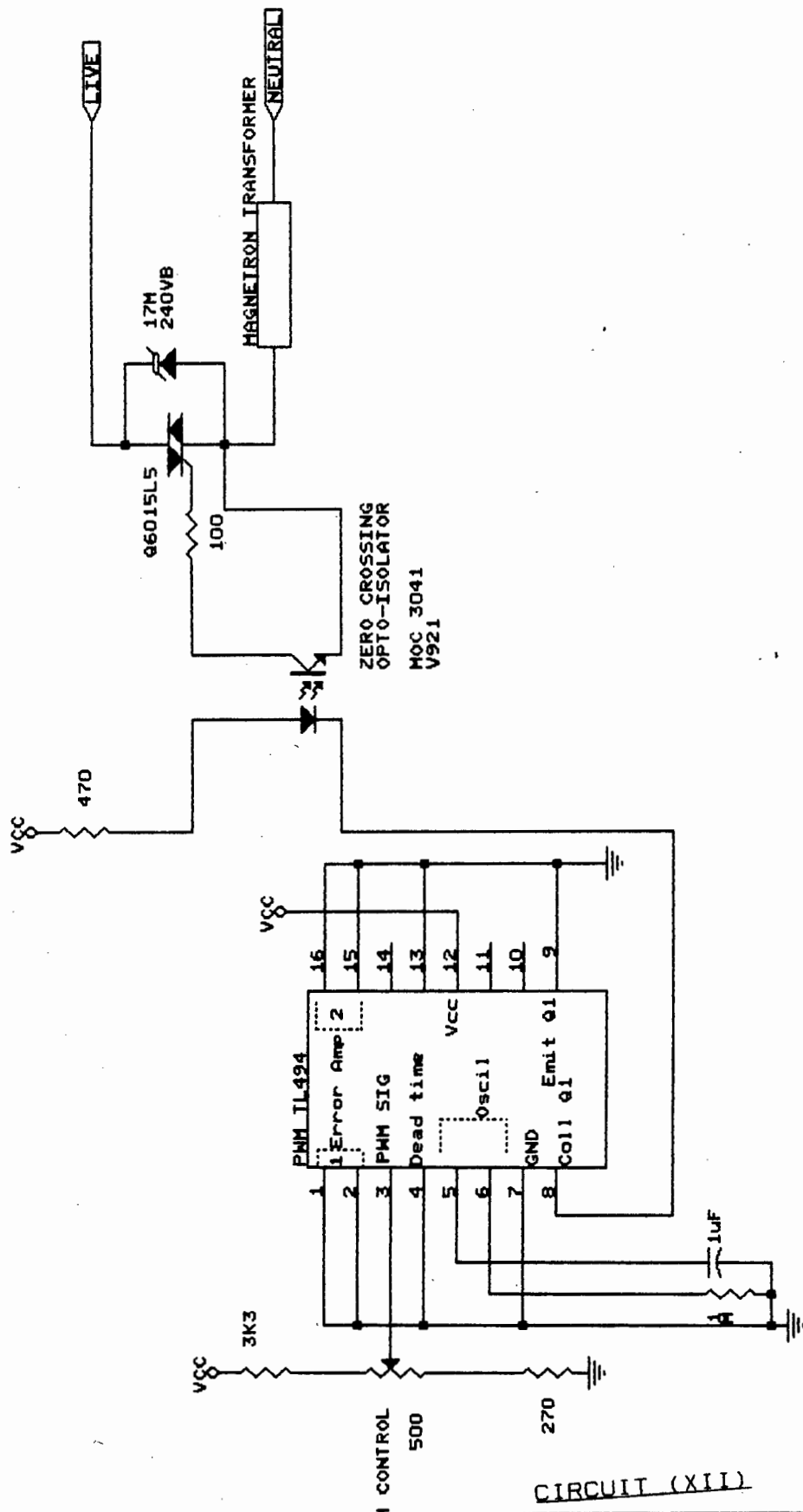
In order to control the output power of the magnetron, an electronic means of power control must be used. Two means of Integral-Cycle-Control have been attempted. These are termed Non-Optimal-Integral-Cycle-Control and Optimal Integral Cycle Control. Integral cycle control allows the supply voltage to be altered by regulating the number of A.C. mains cycles transferred to the load. For example, for 50 cycles / second, if one cycle is transferred to the load, then the new RMS voltage is :

$$\frac{1}{50} \times 220 \text{ V}_{\text{rms}} = 4.4 \text{ V}_{\text{rms}}$$

Non-Optimal Integral Cycle control

This technique allows non-integral cycles (i.e. also half cycles) to be transferred to the load. CIRCUIT (XII) (following page) was built and tested. It uses a TL494 PWM (Pulse-Width-Modulation) I.C. A control voltage alters the pulse-width of a periodic signal. This signal is used to drive a zero-crossing opto-isolator, which in-turn drives a triac (controlling the power supplied to the magnetron-transformer).

Power could be altered using this circuit, but the following problems were encountered. There are increased losses in the transformer (manifested as heat loss), since the magnetic flux in the transformer core does **not** pass **both** ways through the transformer if a half-cycle is delivered to the transformer.



NON-OPTIMAL INTEGRAL CYCLE CONTROL CIRCUITRY

Optimal Integral Cycle control

By sensing the mains voltage; this technique **only** allows full-cycles to be transferred to the load. A Plessey SL441 integral cycle control chip was used to control the power supplied to the magnetron-transformer. CIRCUIT (XIII) (following page) was built and tested. The circuit uses separate power supplies to supply power to an isolation amplifier (ISO122P). The isolation amplifier was used so that the controller could be controlled by a computer.

Power can be altered to the load **but**, the following problems exist. The SL441 switches the triac ON, at the zero (voltage) crossing of the A.C. wave. Since the transformer is an inductive load, the current lags the voltage by 90° E (theoretically). Thus, although the voltage is a minimum at switch-ON, the current is a maximum. To lower the surge current, a resistive load has to be placed in parallel with the magnetron transformer. This lowers the phase difference between the current and voltage.



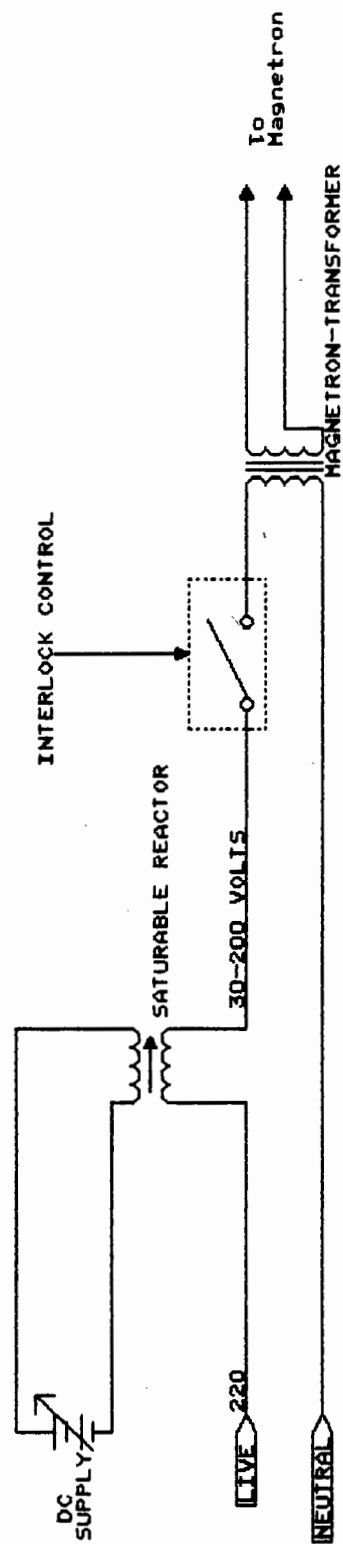
The limitation of this technique is the following. In order to reduce the effect of surge currents through the primary of the transformer, the flux through in the transformer core must be maintained. This implies that the switching period should be reduced. For example, instead of having a timing period of 1 second (and altering the number of cycles within this period), a shorter timing period should be used. However, by reducing the timing period, the voltage control resolution is reduced e.g. if a 500 mSec timing period is used, then the best voltage control resolution obtainable is :

$$\frac{1}{25} \times 220 \text{ V}_{\text{rms}} = 8.8 \text{ V}_{\text{rms}}$$

10.5.3 Saturable reactor

In an attempt to achieve better output power control, another Power Control technique has been used to alter the supply voltage to the **magnetron-transformer**. FIGURE (XIV) (following page) shows the interconnection of the **saturable reactor** and the **magnetron-transformer**.

The saturable reactor acts as a variable inductance (it's inductance being controlled by a DC control current in its primary winding). This technique is better than integral-cycle-control since the AC sine wave is not "broken up" (this causes the creation of odd harmonics in the transformer which increase transformer losses), but the AC sine wave is attenuated.



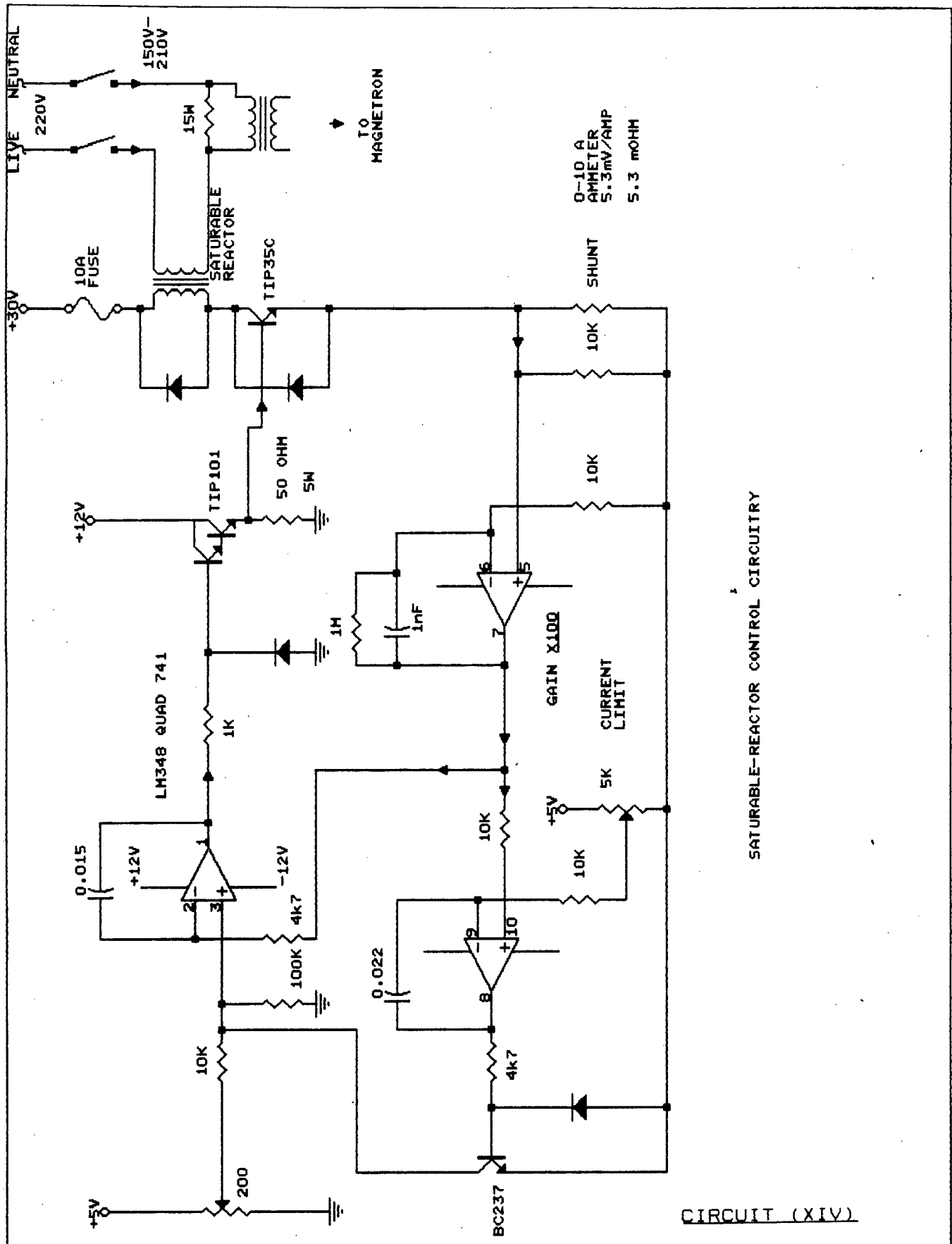
CONCEPTUAL DIAGRAM ILLUSTRATING SATURABLE REACTOR
CONNECTION TO MAGNETRON-TRANSFORMER

FIGURE (XV)

The DC supply current in the primary winding is controlled by Circuit (XV).

The circuit was designed around an LM348 (QUAD 741) opamp. The current flowing through the primary of the saturable reactor (and through the 5.3mOhm SHUNT resistance) is sensed (converted to a voltage) and this voltage is used in a feedback loop to accurately control the current. As added protection, a CURRENT LIMIT has been built into the circuit. By adjusting the CURRENT LIMIT potentiometer, the maximum allowable current through the saturable reactor can be fixed.

Adjustment of the current through the primary of the saturable reactor results in the supply voltage to the magnetron-transformer being altered from 30 Volts to 200 Volts. This allows for continuous control of the output power of the magnetron.



11. MICROWAVE MILK UNIT

The physical construction of the MMP is discussed in this chapter. It discusses the **Choice of materials** (metals , plastic, glass) followed by a description of the unit construction and practical layout considerations (for safety purposes).

11.1 Choice of materials for MMP construction

Figure (XVI) (See following page) shows the basic MMP design.

In accordance with hospital regulations, the metal used in the construction of equipment used in the hospital should preferably be **GRADE 316 ST/ST (stainless steel)**. Thus, with reference to Figure (XVI), the Transformer & Magnetron Housing, Controller Housing, Extrusion piping (used to secure the milk container) and the cylindrical tube surrounding the PTFE container are also made with **GRADE 316 ST/ST**. The Level sensor probes are made of **GRADE 316 ST/ST**. The Pt100 has a Superior Corrosion Resistance with a low carbon 316 ST/ST sheath.

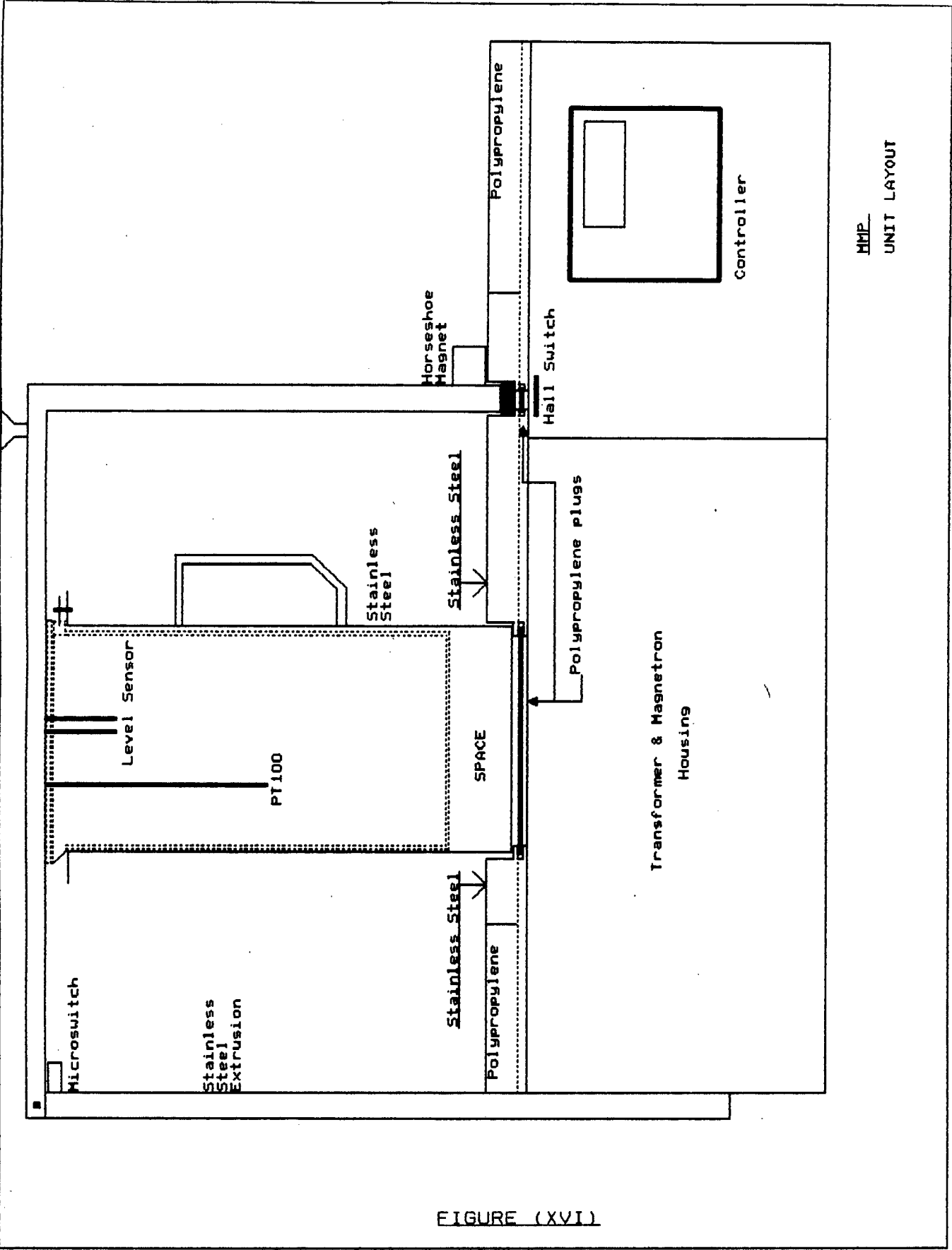


FIGURE (XVI)

The use of Boro-silicate glass and a number of plastic (PTFE - Teflon, Nylon, PVDF, Co-polymer Acetylene and High Density Polyethylene) for the milk container were considered. The use of glass as the milk container was discounted due to the adhesion of milk components onto the glass. After comparing plastic properties, their costs, their availability, their ability to be fashioned into a usable container and their propensity to absorb microwave energy (and heat up), PTFE was chosen.



PTFE has the excellent friction properties (hence milk constituents do not stick to the container walls) and good chemical resistance to hot water and weak acids. It is a good heat insulator with a high enough melting point (165 °C). Tests in a microwave oven showed that the teflon did not absorb sufficient microwave energy to heat up. A major factor of consideration in determining the type of plastic was the availability of suitable containers (standard sizes) or the possibility of having a container made. Since local manufacturers are only prepared to make a plastic-mould if large quantities are ordered, a standard teflon container was purchased.

The handle on the milk container is made of polypropylene. Stainless Steel screws are used to secure sections of the MMP together.

11.2 Unit housing and structural design

The MMP is designed to prevent ingress of liquids (due to spillage and leakage) into the containments housing the LIVE electrical wires. It is designed so that the milk container is secured in place and so that, should the milk container be removed, the magnetron will stop emitting power immediately.

The following figures show the dimensions of the MMP unit components.

Figures (XVII),(XVIII) and (XIX) show the drawings of the LAUNCH WAVEGUIDE, TUNING SCREW WAVEGUIDE and QUARTER-WAVE TRANSFORMER WAVEGUIDE's respectively. All are made of brass.

MMP
S.C. MICHELSON
MATERIAL 1 BRASS
LAUNCH GUIDE DIMENSIONS

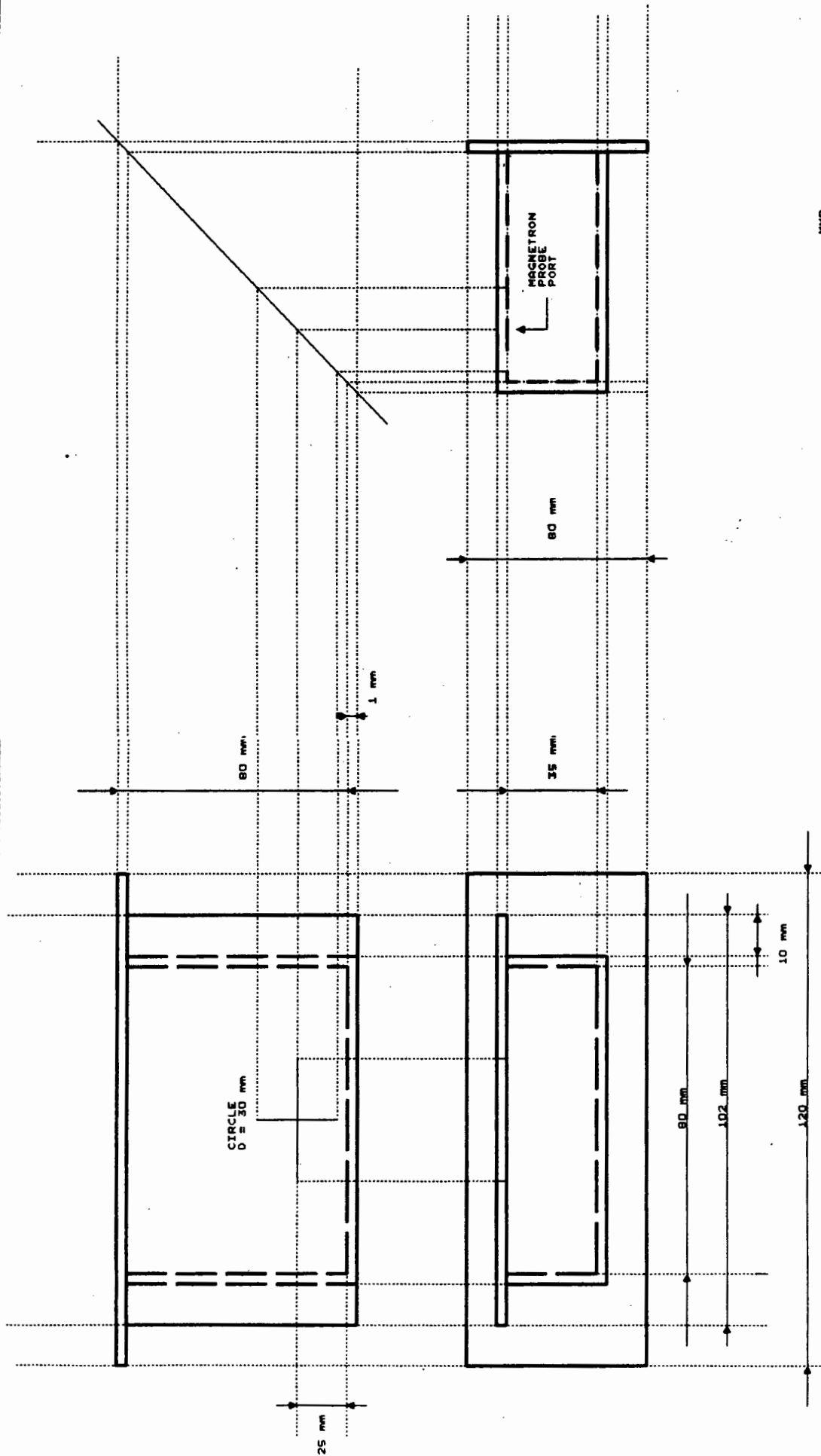


FIGURE (XVII)

MRP
 S.C. MICHELSON
 MATERIAL : BRASS
 TUNING-SCREW WAVEGUIDE DIMENSIONS

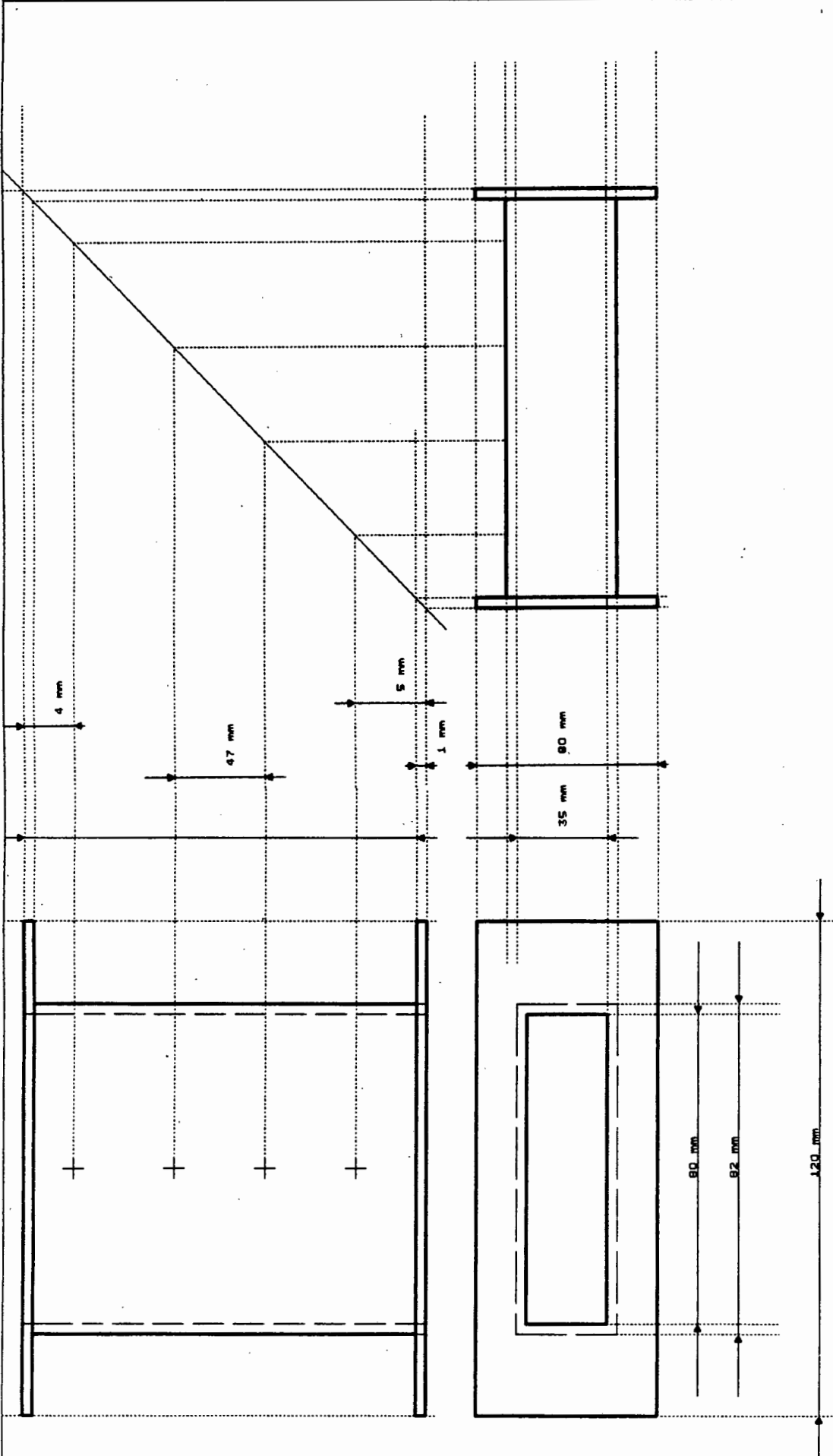


FIGURE (XVIII)

MMP
S.C. MICHELSON
MATERIAL : BRASS
QUARTER-WAVE TRANSFORMER
DIMENSIONS

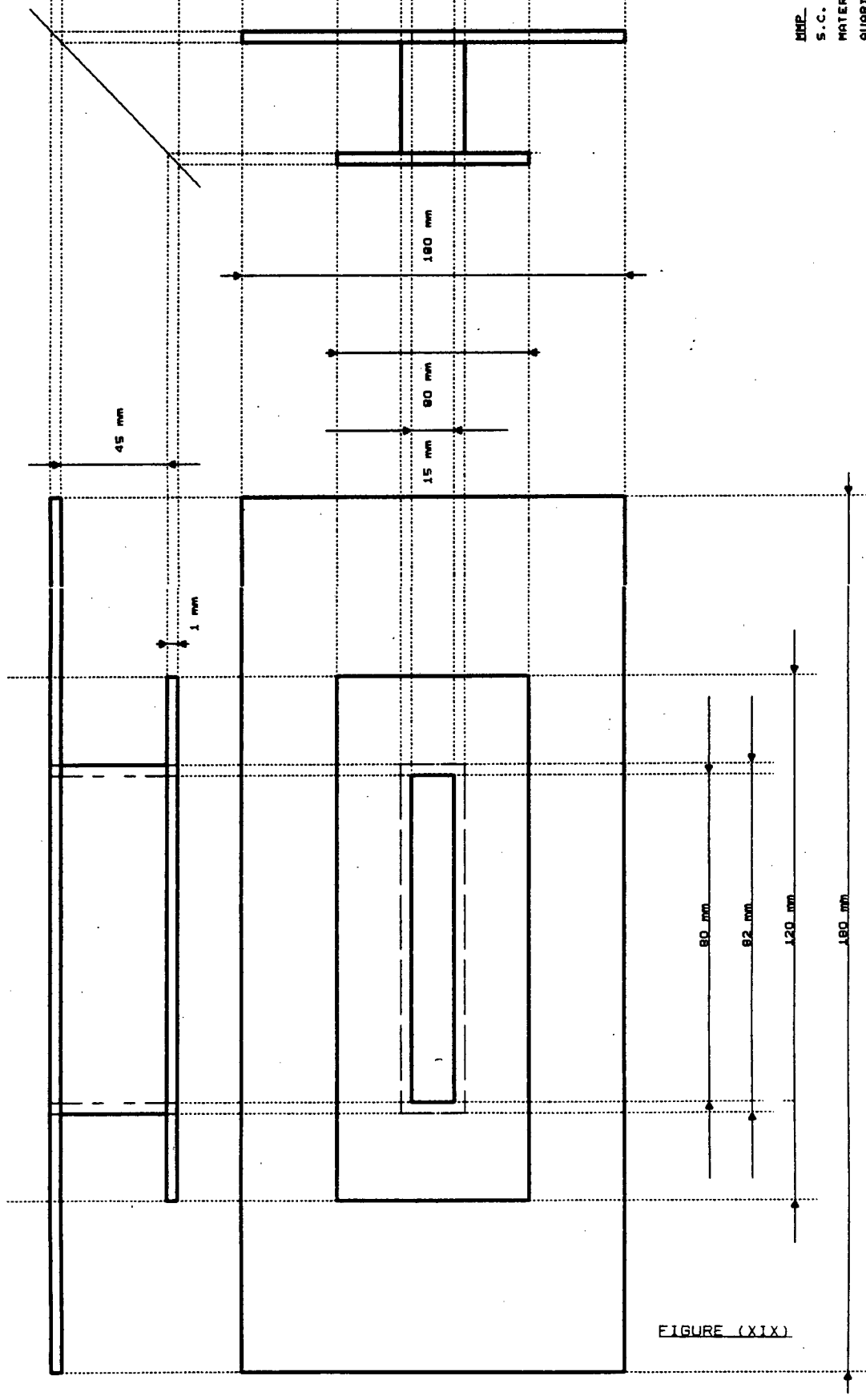
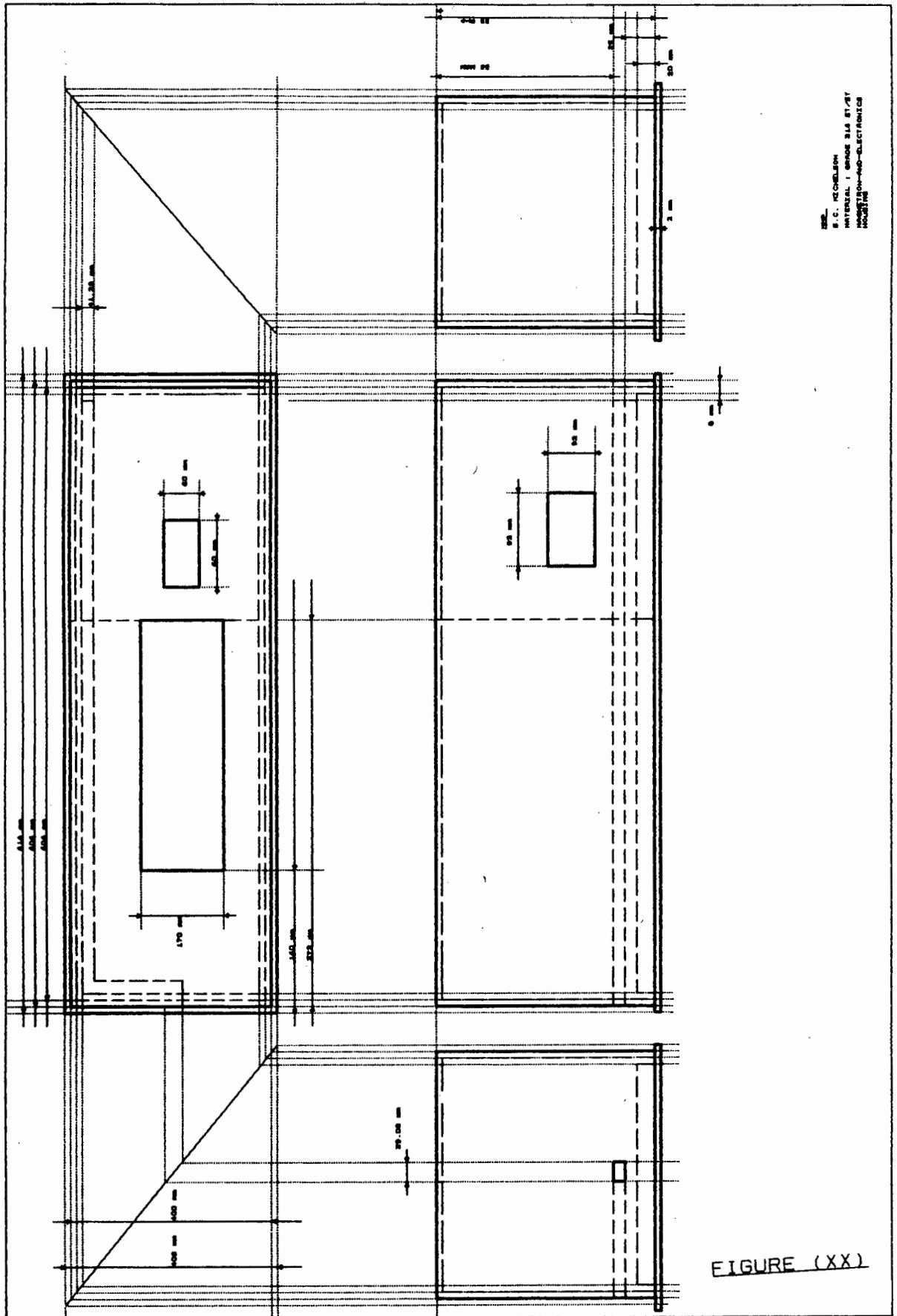


FIGURE (XIX)

Figure (XX) is a drawing of the TRANSFORMER-AND-MAGNETRON HOUSING. It has a (92 mm x 92 mm) hole on the front for a control panel. On top, there are two holes. One each for the waveguide and for the Hall switch. The housing is made of GRADE 316 ST/ST. The bottom of the housing is designed so that no spilt liquid can enter the housing. Further, there is a built-in conduit for the electrical wiring (made of steel extrusion (41.28 x 41.28 mm)). The electronics section and the electrical section (housing the magnetron-transformer) are separated by a panel. The panel is used to prevent electrical interference (resulting from transformer switching) from affecting the electronic circuitry. The conduit links the electronics section to the electrical section.

Figure (XXI) shows a drawing of the Polypropylene-Cover which is placed on top of the MMP's TRANSFORMER-AND-MAGNETRON HOUSING. Figure (XXII) shows a drawing of the Stainless Steel Placement-Cover which fits inside the Polypropylene-Cover. The Placement-Cover is used to secure the PTFE CONTAINER HOUSING (Figure (XXIII)) and the EXTRUSION ENCLOSURE piping which hold the magnet (activates the HALL SWITCH). Figure (XXIV) shows the EXTRUSION ENCLOSURE (The PTFE CONTAINER LID is attached to the EXTRUSION ENCLOSURE { the Pt100 and Level Sensor probes are placed through the LID }) . Figure (XXV) shows the ST/ST Extrusion which contains the wires (coming from the Micro Switch, Pt100 and Level Sensor probes). The microswitch is secured onto the ST/ST Extrusion with a ST/ST bracket.



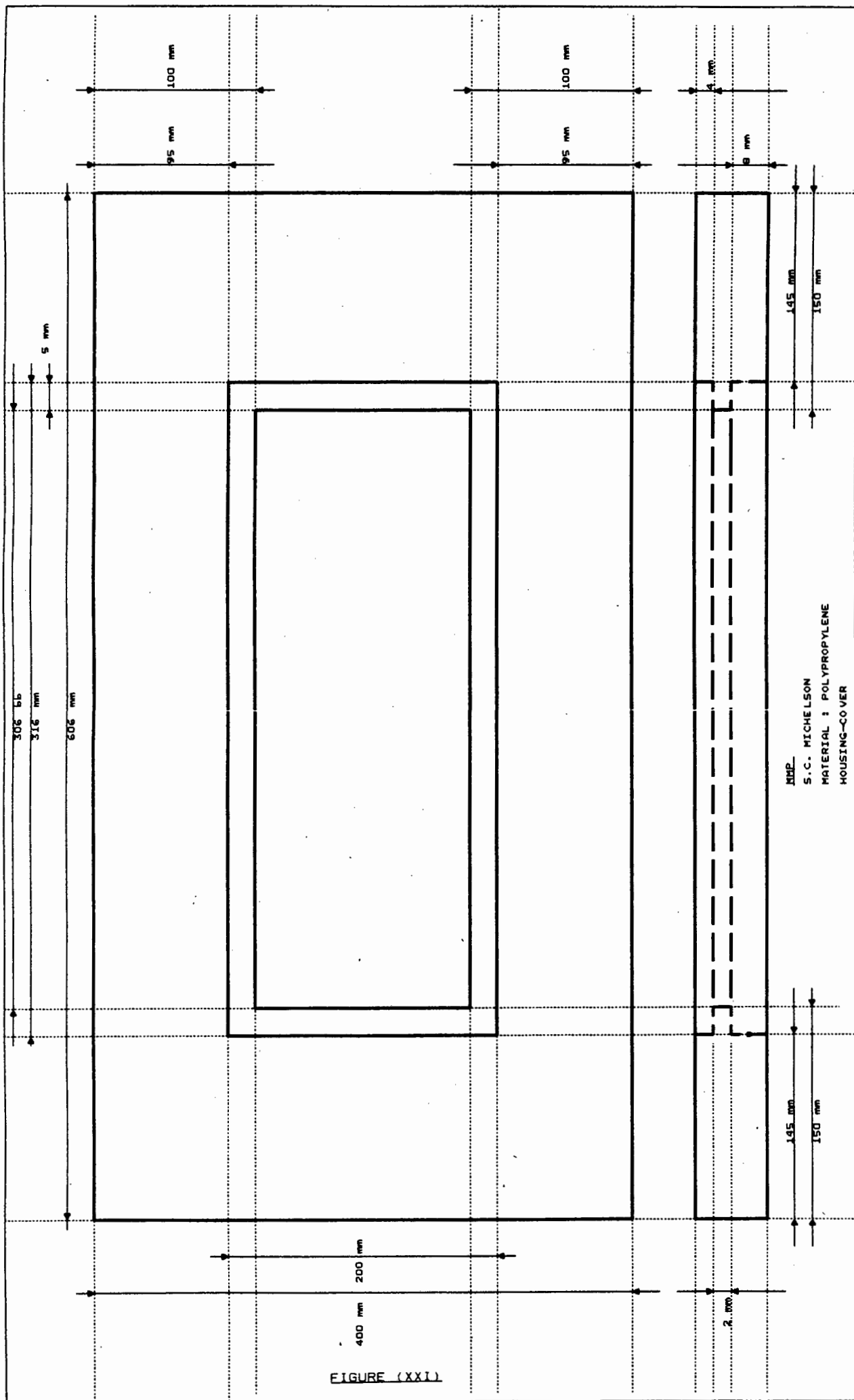


FIGURE (XXI)

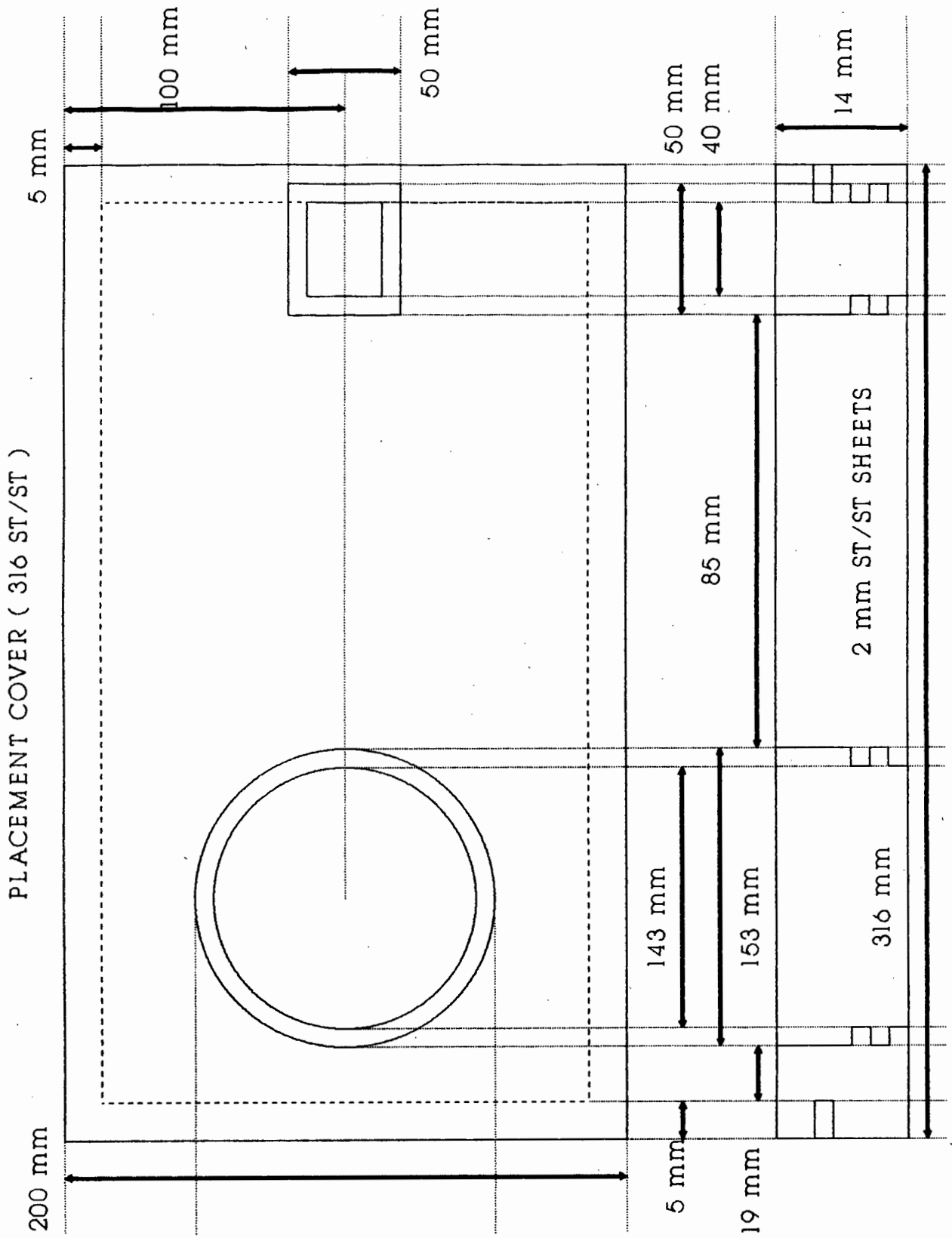


FIGURE (XXII)

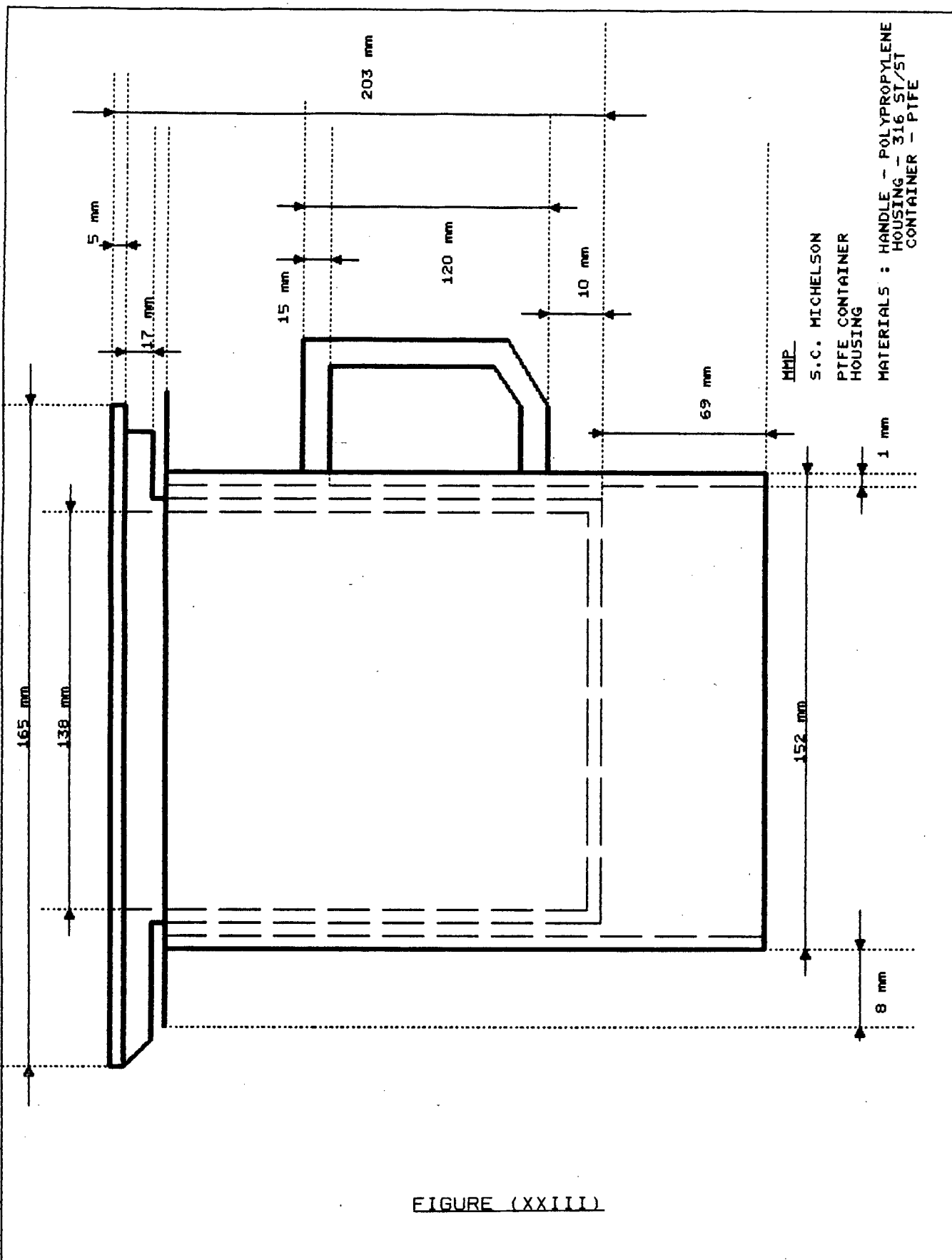
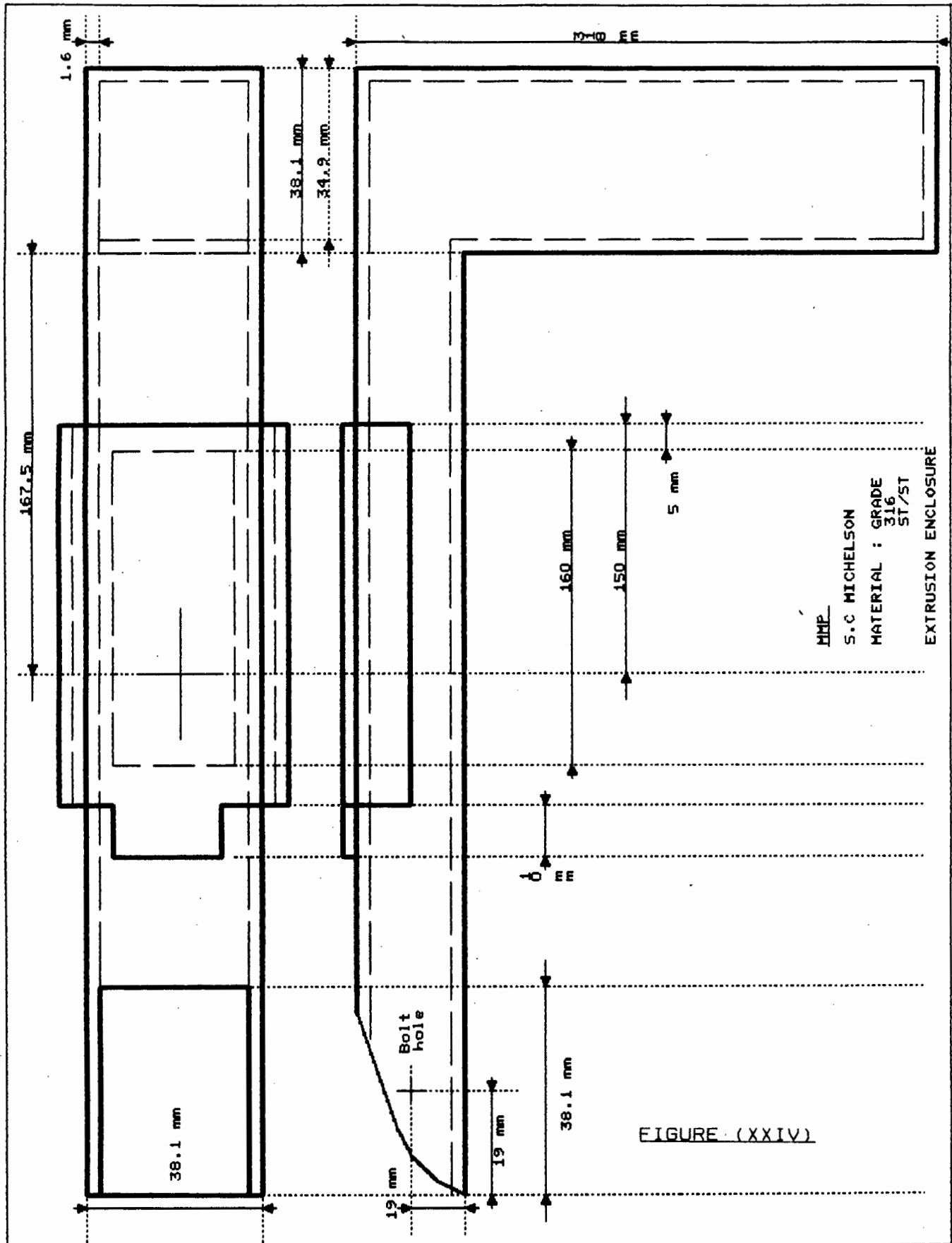
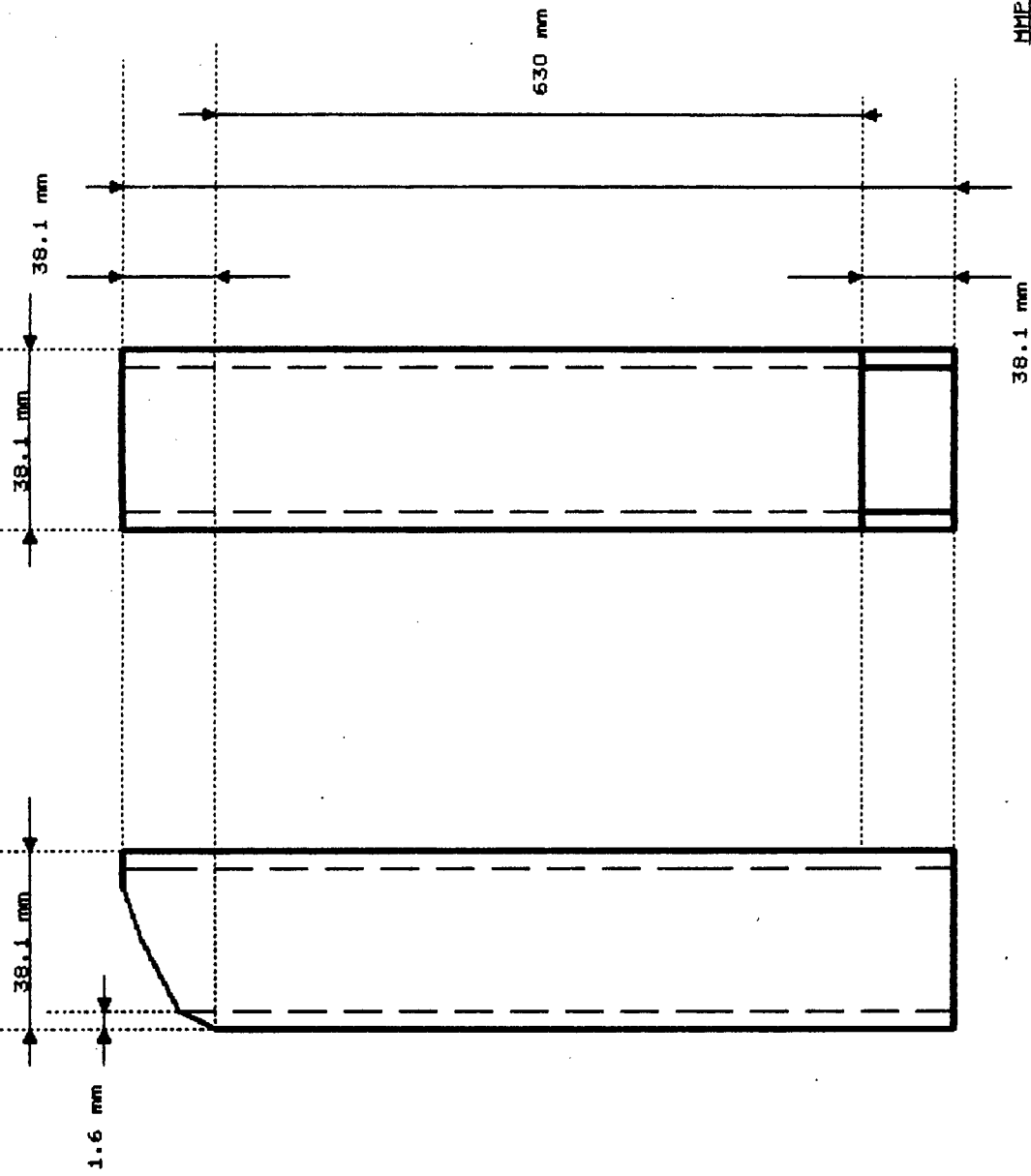


FIGURE (XXIII)





आम

S.C. MICHELSON
MATERIAL : GRADE 316
ST/ST EXTRUSION

FIGURE (XXV)

12. CONCLUSIONS

The AIDS virus can be transferred from an AIDS infected lactating mother into her milk. This milk, once pooled, could be used to feed premature infants. It is preferred that premature infants are fed with breast milk since they risk possible hazards when fed with commercial milk formulas. These include:

- 1: The possibility of serious infection.
- 2: The dangers of intravenous lines.
- 3: Embolisms (blockage of arteries).
- 4: Metabolic disturbance.

Two expensive pasteurizers, designed in England exist which destroy the virus. These are the :

- 1: The 'Oxford' pasteuriser by Vickers Medical (R45 000).
- 2: The 'Axicare' pasteuriser by Colgate Medical (R42 000).

The estimated production cost of a locally made pasteurizer (MMP) is of the order of R10 000.

The virus can be destroyed by pasteurizing the milk. This is done if the temperature of the milk is uniformly maintained at (56-57.5) °C for 33 min.

Pasteurization of pooled breast milk means:

- 1: The elimination of the risk of HIV transmission .
- 2: Screening for HIV antibodies becomes unnecessary.
- 3: The babies don't have to be exposed to the possible dangers of being fed with preterm milk formulas.

Heating methods using (hot elements or water-baths) apply heat (a disordered form of energy) externally.

Microwaves make use of Electromagnetic energy a (highly ordered form of energy) to facilitate the generation of heat internally. The advantages of using microwaves over it's alternatives include :

- 1: Microwaves energy is an ordered form of energy that is controllable i.e. one can have instant ON/OFF control.
- 2: There is no thermal inertia from the energy source i.e. magnetron (if the cathode heating element is kept ON).
- 3: The energy transfer mechanism is the most efficient.
- 4: The milk need not come into contact with any water (in a water-bath possibly containing bacteria harmful to a preterm baby), plastic (except the container in which it is housed) or metal element which may be susceptible to corrosion.
- 5: By proper selection and design of the microwave applicator, the energy can be focussed onto the milk.

- 6: The microwaves have a sterilisation effect (in so far as deactivating harmful bacteria) which is vastly better than the sterilization ability of other heating techniques.
- 7: Energy is not expended in heating the housing containing the breast milk.

In order to make and sell an item of microwave equipment, certain safety conditions have to be fulfilled. Once the equipment is made and tested, an application for a licence must be made to the Director-General in writing.

Safety considerations have to be adhered to for:

- 1 : Electrical safety. Electrical safety requirements are laid out by the IEC (B.S. 5724 Part 1 1979) (this is a set of requirements for medical equipment).
- 2: Microwave radiation safety. Safety requirements are laid out in a draft copy of a document produced by the The Division of Radiation Control of the Department of Health. This document has not been published as information contained in it is still being revised.
3. Unit construction safety. IEC (B.S. 5724 Part 1 1979)

As a result of water being a major constituent of milk and being polar, it's propensity to absorb microwave energy at microwave frequencies is enhanced. As a result of the water being a dielectric, it's energy absorption mechanism can theoretically be described if it's permittivity is characterized.

The permittivity (a constant which is comprised of two components (dielectric constant - ϵ_r') and (dielectric loss - ϵ_r'')) of a material is a function of :

- 1 : The material temperature.
- 2 : The **time history** of material temperature and applied electric field .
- 3 : The position of the incident electric field on the medium being heated.
- 4 : The frequency of the microwaves which are incident on the milk.

The characteristic impedance of the milk is a function of its permittivity. Calculations show that for an 80 °C change in load temperature :

- 1 : The reactive component of the water's impedance is negligible compared to the it's resistive component.
- 2: The resistive component of the water **only** varies by approximately 10 Ω .
- 3: The impedance of milk can be **approximated** to that of water.

The single-mode applicators have advantages over multi-mode applicators in terms of their :

- 1 : Uniformity of heating
- 2 : Ease of temperature measurement.

A waveguide has been designed which can optimally couple power into breast milk. For uniform transfer of energy into the milk, the TE_{11} (circular) is incident on the milk.

A Platinum element (Pt100) RTD (Resistance Temperature Detector) is used due to it's :

- 1 : Superior accuracy.
- 2 : Linearity.
- 3 : Stability.

The Pt100 is placed perpendicular to the Electric field so that there is minimal electrical noise induced by the microwaves.

There are two electrical safety interlocks:

- 1 : A LEVEL sensor ensures the milk container is adequately filled.
- 2: A HALL SWITCH must be ACTIVE (occurs when the container is closed).

There is one mechanical interlock :

- 1: A MICROSWITCH which must be closed.

When the interlocks are active, the microwave power can be applied. If the TIMER signal from the timing circuitry is not ACTIVE, then the magnetron cannot be activated. This ensures :

- 1 : The device cannot be left ON for an indiscriminately long period.
- 2: The milk temperature is maintained in the required temperature band for the correct time (not longer).

Extra safety features include:

- 1: A DP DT switch on the supply.
- 2: Fusing of the LIVE and NEUTRAL conductors.
- 3: A thermal CUT-OUT attached to the magnetron.
- 4: A relay configuration which causes immediate extinction of power emission from the magnetron when any of the interlocks are DEACTIVATED.

Continuous microwave power control can be achieved if the supply voltage to the magnetron is altered. This has been verified by tests performed using a Variac. Optimal and Non-Optimal Integral-Cycle-Control techniques have been tried in order to alter input power to the magnetron-transformer. These methods have been disqualified for use in the MMP because :

- 1 : Excessive transformer heating arises due to the presence of odd-harmonics introduced due to switching.
- 2: There is an unsatisfactory control voltage resolution.
- 3: Switching of the inductive load results in large surge-currents which result in excessive transformer heating.

The saturable reactor can continuously control the supply voltage to the magnetron-transformer. This means that accurate control of the magnetrons **Output power** can be achieved. Excessive transformer heating does **not** arise (since the harmonics introduced due to saturation in the saturable reactor core are not sufficiently large).

The materials chosen to make the MMP are:

- 1 : The metal (level sensor probes, RTD, electrical circuitry housing) is GRADE 316 Stainless steel.
- 2 : The milk container is made of Teflon. The milk container handle is made of polyethylene.
- 3 : The waveguide sections are made of brass.

The MMP has been designed to prevent ingress of liquids due to spillage or leakage.

The diagrams for the construction of the MMP housing have been completed.

13. RECOMMENDATIONS

Based on the conclusions drawn in this dissertation, the following recommendation have been drawn :

- 1 : The saturable reactor must be used for the voltage control of the magnetron.
- 2 : The cathode heating element must have it's own supply.
- 3 : In view of the fact that the magnetron has a **linear** Output power vs Supply voltage characteristic (when the supply operates in the (150-200 V) range) , an attempt can be made achieve temperature control using a linear controller (the controller should limit the supply to the Magnetron-transformer to the above range).
- 4: The final housing of the MMP can then be built.

14. APPENDIX A

The theoretical derivation for the difference in reflection coefficient resulting from a change in impedance:

$$\begin{aligned}
 p'_{11} - p'_{22} &= \frac{(Z_{11} - Z_0)}{(Z_{11} + Z_0)} - \frac{(Z_{12} - Z_0)}{(Z_0 + Z_{12})} \\
 &= \frac{(Z_{11} - Z_0)(Z_0 + Z_{12}) - (Z_{11} + Z_0)(Z_{12} - Z_0)}{(Z_{11} + Z_0) \cdot (Z_0 + Z_{12})} \\
 &= \frac{\{(Z_{11} \cdot Z_{12} - Z_0 \cdot Z_{12} + Z_0 \cdot Z_{11} - Z_0^2)\}}{(Z_{11} + Z_0) \cdot (Z_0 + Z_{12})} \\
 &\quad - \frac{(Z_{11} \cdot Z_{12} - Z_0 \cdot Z_{11} + Z_0 \cdot Z_{12} + Z_0^2)}{(Z_{11} + Z_0) \cdot (Z_0 + Z_{12})} \\
 &= \frac{2 \cdot Z_0 \cdot (Z_{11} - Z_{12})}{(Z_0 + Z_{11}) \cdot (Z_0 + Z_{12})}
 \end{aligned}$$

15. APPENDIX B15.1 Solutions of wave equations

The electric and magnetic wave equations for propagating waves in rectangular and circular (or any other shaped) waveguides are derived from the solutions of Maxwell's vector wave equations. They are the derived from the solutions of :

$$\nabla^2 E = \Gamma^2 E$$

$$\nabla^2 H = \Gamma^2 H$$

where :

$$\Gamma = \alpha + j \cdot \beta$$

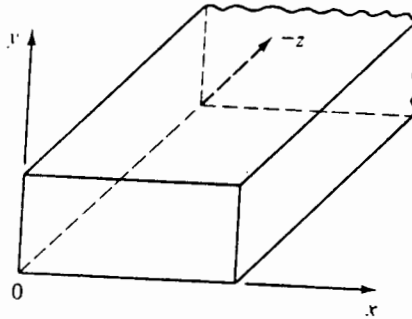
Γ = propagation constant.

α = attenuation constant.

β = wave number.

15.2 TE modes in Rectangular Waveguides

Considering the following diagram.



The waves propagate in the positive z direction. The TE_{mn} modes in a rectangular guide are characterized by $E_z = 0$. Thus, the z component of the magnetic field H_z , must exist for energy transmission down the line. Therefore, one must solve the Helmholtz equation

$$\nabla^2 H_z = \Gamma^2 H$$

to find the solutions of the E and H fields in the waveguide.

These are [29]:

$$E_x = E_{0x} \cdot \cos \left[\frac{m \cdot \pi \cdot x}{a} \right] \cdot \sin \left[\frac{n \cdot \pi \cdot y}{b} \right] e^{-j\beta z}$$

$$E_y = E_{0y} \cdot \sin \left[\frac{m \cdot \pi \cdot x}{a} \right] \cdot \cos \left[\frac{n \cdot \pi \cdot y}{b} \right] e^{-j\beta z}$$

$$E_z = 0$$

$$H_x = H_{0x} \cdot \sin \left[\frac{m \cdot \pi \cdot x}{a} \right] \cdot \cos \left[\frac{n \cdot \pi \cdot y}{b} \right] e^{-j\beta z}$$

$$H_y = H_{0y} \cdot \cos \left[\frac{m \cdot \pi \cdot x}{a} \right] \cdot \sin \left[\frac{n \cdot \pi \cdot y}{b} \right] e^{-j\beta z}$$

$$H_z = H_{0z} \cdot \cos \left[\frac{m \cdot \pi \cdot x}{a} \right] \cdot \cos \left[\frac{n \cdot \pi \cdot y}{b} \right] e^{-j\beta z}$$

$$m = 0, 1, 2, \dots$$

$$n = 0, 1, 2, \dots$$

The cutoff wavenumber k_c for TE_{mn} modes is :

$$k_c = \sqrt{\left[\frac{m \cdot \pi}{a}\right]^2 + \left[\frac{n \cdot \pi}{b}\right]^2} = \omega_c \cdot \sqrt{\mu \cdot \epsilon}$$

where a, b are in meters

$$\text{and } k_x = \frac{m \cdot \pi}{a} \quad k_y = \frac{n \cdot \pi}{b}$$

$$\sqrt{\epsilon \cdot \mu} = \sqrt{\epsilon_r \cdot \mu_r \cdot \epsilon_0 \cdot \mu_0}$$

The cutoff frequency for the TE_{mn} modes is :

$$f_c = \frac{1}{\sqrt{\mu \cdot \epsilon}} \cdot \sqrt{\left[\frac{m}{a}\right]^2 + \left[\frac{n}{b}\right]^2}$$

The guide wavelength for the propagating modes is :

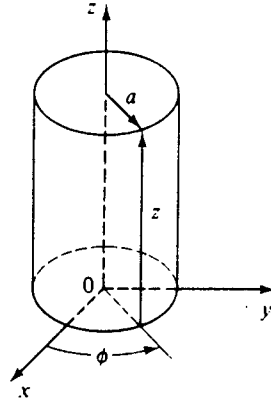
$$L_g = \frac{L_0}{\sqrt{1 - \left[\frac{L_0}{L_c}\right]^2}} = \frac{L_0}{\sqrt{1 - \left[\frac{f_c}{f_0}\right]^2}}$$

The characteristic wave impedance for the TE_{mn} modes is :

$$\begin{aligned}
 Z_g &= \frac{w \cdot \mu}{\beta} = \frac{b}{a} \cdot \frac{Z_o}{\sqrt{1 - \left[\frac{f_c}{f_o} \right]^2}} = \frac{b}{a} \cdot \frac{Z_o}{\sqrt{1 - \left[\frac{L_o}{L_c} \right]^2}} \\
 &= Z_o \cdot \frac{b}{a} \cdot \frac{L_g}{L_o}
 \end{aligned}$$

15.3 TE modes in Circular Waveguides

The following diagram shows the coordinates in a circular waveguide.



If the waves in a circular waveguide are assumed to propagate in the positive z direction. The TE_{np} modes in a circular guide are characterized by $E_z = 0$. Thus, the z component of the magnetic field H_z must exist for energy transmission down the line. Therefore, one must solve the Helmholtz equation below for the circular waveguide :

$$\nabla^2 H_z = -\Gamma^2 H_z$$

Its solution is given by :

$$H_z = H_{0z} \cdot J_n(k_c \cdot r) \cdot \cos(n \cdot \phi) \cdot e^{-j\beta z}$$

which is subject to given boundary conditions.

$J_n(k_c \cdot r)$ is the n 'th-order Bessel function of the First Kind representing a standing wave of $\cos(k_c \cdot r)$ for $r < D/2$. D is the diameter of the circular waveguide.

The boundary conditions

are that

$$E_z = 0 \text{ at } r = R \text{ thus } \left. \frac{\delta H_z}{\delta r} \right|_{r=D/2} = 0$$

or

$$E_r = 0 \text{ at } r = D/2 \text{ thus } \left. \frac{\delta H_z}{\delta r} \right|_{r=D/2} = 0$$

This means that:

$$\left. \frac{\delta H_z}{\delta r} \right|_{r=D/2} = H_{0z} \cdot J_n'(k_c \cdot r) \cdot \cos(n \cdot \phi) \cdot e^{-j\beta z}$$

hence :

$$J_n'(k_c \cdot D/2) = 0$$

where J_n' is the derivative of J_n .

Since J_n' are oscillatory functions, so are $J_n'(k_c \cdot D/2)$.

There are in fact an infinite sequence of values of

$(k_c \cdot D/2)$ which satisfy $J_n'(k_c \cdot D/2) = 0$. The

permissible values of k_c may be written as :

$$k_c = \frac{x'_{np}}{D/2}$$

The table below tabulates a few roots of $J'_n(k_c \cdot D/2)$.

pth ZEROS OF $J'_n(k_c a)$						
p	n					
	0	1	2	3	4	5
1	3.832	1.841	3.054	4.201	5.317	6.416
2	7.016	5.331	6.706	8.015	9.282	10.520
3	10.173	8.536	9.969	11.346	12.682	13.987
4	13.324	11.706	13.170			

TABLE (VI)

The field equations for the TE_{np} modes in a circular waveguide are [29]:

$$E_r = E_{or} \cdot J_n \left[\frac{X'_{np} \cdot r}{D/2} \right] \cdot \sin [n\phi] \cdot e^{-j\beta z}$$

$$E_\phi = E_{o\phi} \cdot J'_n \left[\frac{X'_{np} \cdot r}{D/2} \right] \cdot \cos [n\phi] \cdot e^{-j\beta z}$$

$$E_z = 0$$

$$H_r = - \frac{E_{o\phi}}{Z_0} \cdot J'_n \left[\frac{X'_{np} \cdot r}{D/2} \right] \cdot \cos [n\phi] \cdot e^{-j\beta z}$$

$$H_\phi = \frac{E_{or}}{Z_0} \cdot J_n \left[\frac{X'_{np} \cdot r}{D/2} \right] \cdot \sin [n\phi] \cdot e^{-j\beta z}$$

$$H_z = H_{oz} \cdot J_n \left[\frac{X'_{np} \cdot r}{D/2} \right] \cdot \cos [n\phi] \cdot e^{-j\beta z}$$

where $n = 0, 1, 2, \dots$

$p = 1, 2, 3, \dots$

The cutoff frequency for TE modes in a circular guide is given by :

$$f_c = \frac{X'_{np}}{\pi \cdot D \cdot \sqrt{(\epsilon \cdot \mu)}}$$

$$\text{where: } \sqrt{(\epsilon \cdot \mu)} = \sqrt{(\epsilon_r \cdot \mu_r \cdot \epsilon_0 \cdot \mu_0)}$$

The guide wavelength for the propagating modes is :

$$L_g = \frac{L_o}{\sqrt{1 - \left[\frac{L_o}{L_c} \right]^2}} = \frac{L_o}{\sqrt{1 - \left[\frac{f_c}{f_o} \right]^2}}$$

The characteristic wave impedance for the TE_{np} modes is :

$$Z_g = \frac{Z_o}{\sqrt{1 - \left[\frac{f_c}{f_o} \right]^2}} = \frac{Z_o}{\sqrt{1 - \left[\frac{L_o}{L_c} \right]^2}}$$

$$= \frac{\omega \cdot \mu_o}{\beta}$$

where :

$$\beta = \sqrt{[(2 \cdot \pi \cdot f)^2 \cdot \mu_o \cdot \epsilon_o - (2 \cdot X_{np}/D)^2]}$$

16. APPENDIX CDetermination of HYSTERESIS Voltage

Consider CIRCUIT (XV) (following page).

When V_o is HIGH (V_{cc}), then the threshold at which the comparitor switches is V_{+h} :

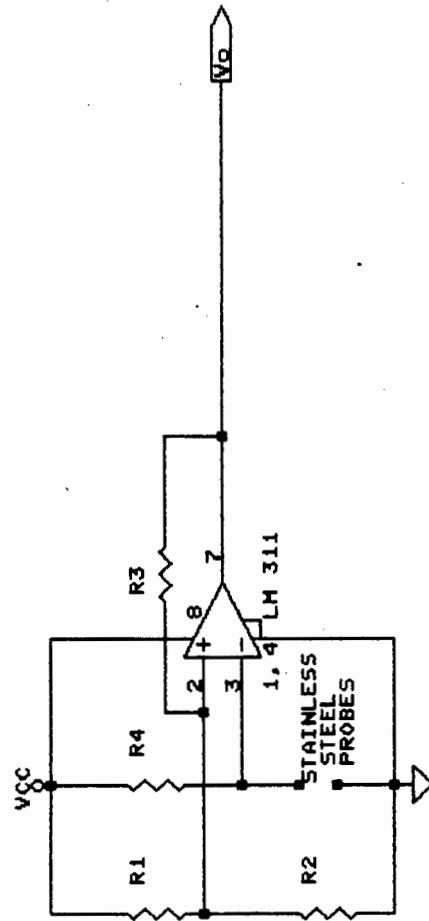
$$V_{+h} = \frac{R_2}{R_1 // R_3 + R_2} \cdot V_{cc}$$

When V_o is LOW (GND), then the threshold at which the comparitor switches is V_{+l} :

$$V_{+l} = \frac{R_2 // R_3}{R_2 // R_3 + R_1} \cdot V_{cc}$$

The hysteresis voltage is :

$$\begin{aligned} V_{hyst} &= V_{+h} - V_{+l} = \left[\frac{R_2}{R_1 // R_3 + R_2} - \frac{R_2 // R_3}{R_2 // R_3 + R_1} \right] \cdot V_{cc} \\ &= \frac{R_1 \cdot R_2}{R_3 \cdot (R_1 + R_2) + R_1 \cdot R_2} \end{aligned}$$

COMPARATOR WITH FEEDBACK
FOR HYSTERESIS

CIRCUIT (XV)

17. APPENDIX DCD4541 CONFIGURATION

The timing period of the 4541's internal oscillator is determined by the choice of R_{tc} and C_1 (SEE CIRCUIT (VII)).

The period of the internal oscillator is :

$$T_{osc111} = 2.3 \times R_{tc} \times C_1$$

Depending on the inputs to A and B on the 4541, (either $(A,B) = (0,0)$ for water or $(A,B) = (1,1)$ for milk), the number of counts is set.

For $(A,B) = (0,0)$, $n = 13$

For $(A,B) = (1,1)$, $n = 16$

The time taken for Q on the 4541 to remain high is :

$$T_{tot} = T_{osc111} \times Tn^{-1}$$

$$= 2.3 \times R_{tc} \times C_1 \times Tn^{-1}$$

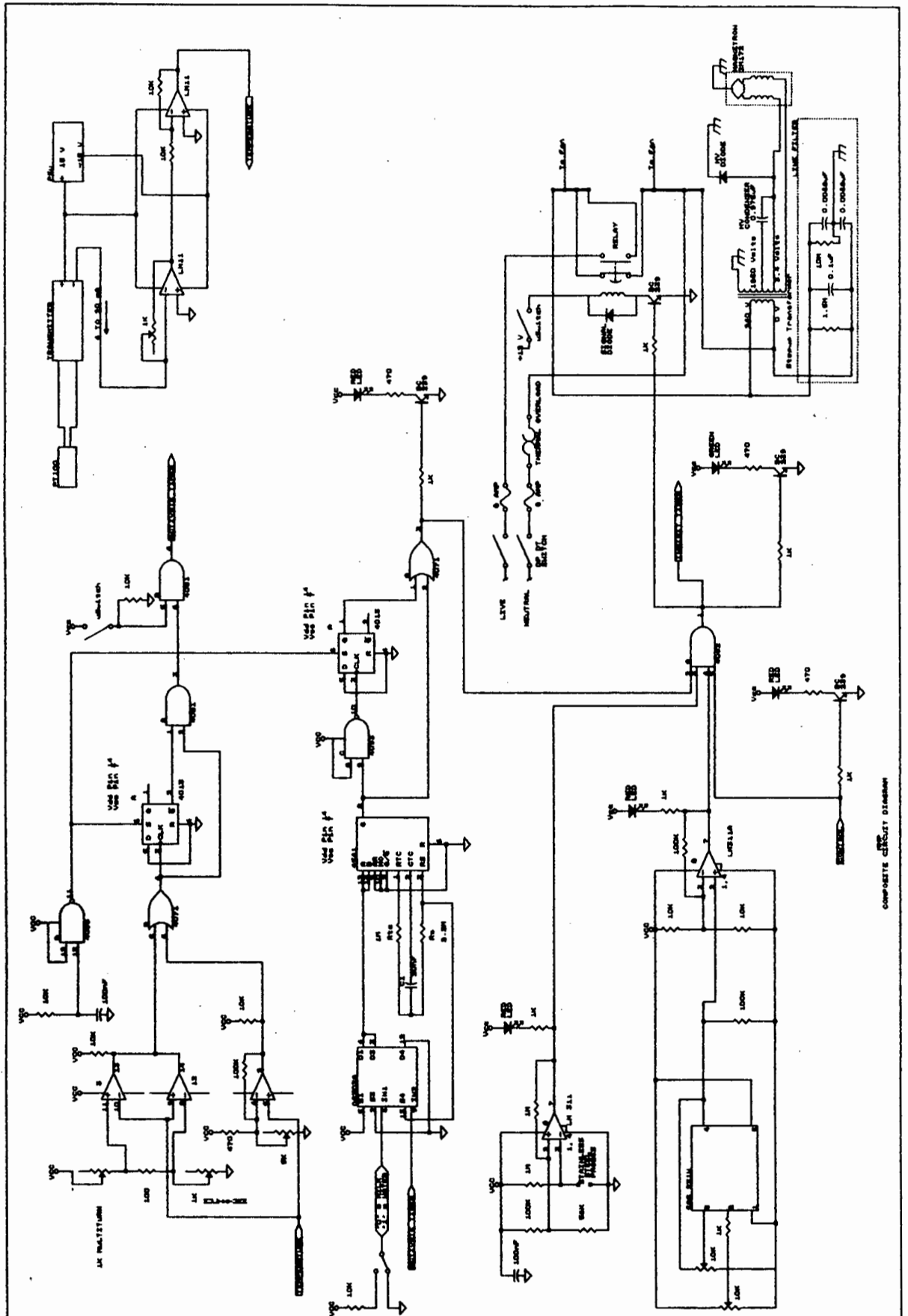
For $R_{tc} = 1.2 \text{ M Ohms}$

$C_1 = 20 \text{ nF}$

$T_{milk} = 30.14 \text{ min.}$

$T_{water} = 1.5 \text{ min.}$

18. APPENDIX E



COMPOSITE CIRCUIT DIAGRAM

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